UNIVERSITY OF OULU

FACULTY OF TECHNOLOGY

A 3D GEOLOGICAL MODEL AND GEOCHEMICAL AND HYDROGEOLOGICAL PROPERTIES OF SEDIMENTS IN KUUSIVAARA, SODANKYLÄ, FINLAND

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Geologinen 3D-malli ja sedimenttien geokemialliset sekä hydrogeologiset ominaisuudet Sodankylän Kuusivaarassa

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Tiivistelmä

Kuusivaara Sodankylässä on suunniteltu sijoituskohde kaivosinfrastruktuurille Anglo Americanin Sakatin Cu-Ni-PGE kaivosprojektissa ja infrastruktuurin suunnittelussa tarvitaan tietoa Kuusivaarassa esiintyvistä kvartäärikerrostumista. Tämä tutkimus pyrki luomaan 3D-mallin Kuusivaaran alueen kvartäärisedimenteistä määrittääkseen alueella esiintyvien eri sedimenttiyksiköiden levinneisyyden. Tämän lisäksi tutkielmassa tutkittiin näiden sedimenttien geokemiallisia ja hydrogeologisia ominaisuuksia.

Tutkielmassa käytetty sedimentologinen aineisto saatiin tutkimuskaivannoista, maaperä- ja turvekairaustiedoista sekä maatutkaprofiileista. Sedimentologisten aineistojen avulla luotiin 3D-malli Leapfrog Geo -ohjelmistolla. Sedimenttien geokemiaa tutkittiin kuningasvesiuutossa alkuaineanalyyseillä, joita tehtiin uusille näytteille ja arkistoiduille moreeninäytteille vuosilta 1973 ja 1975. Metallien ja muiden yhdisteiden liukoisuutta tutkittiin pienellä määrällä näytteitä kaksivaiheisella ravistelutestillä. Sedimenttien vedenläpäisevyydet määritettiin pohjavesikaivoihin tehdyillä slug-testeillä ja arvioimalla vedenläpäisevyyksiä käyttäen empiirisiä kaavoja ja sedimenttinäytteiden raekokojakaumia.

Luotu 3D-malli koostuu yhdeksän yksikköä sisältävästä runkostratigrafiasta, joka luotiin tutkimusalueelle perustuen sedimentologisiin *in situ* -aineistoihin. Stratigrafiassa on listattuna pinnalta alkaen: turve, pintahiekka, ylempi hiekkamoreeni, sora, moreenien välinen hiekka, alempi hiekkamoreeni, silttimoreeni, rapakallio ja kallio. 3D-mallissa ylempi hiekkamoreeni on laajalti ainut sedimenttiyksikkö rapakallion ja kallion yläpuolella Kuusivaarassa turvepeitteisten suoalueiden ulkopuolella. Pintahiekkaa esiintyy rajatuilla alueilla pinnassa sekä laajalti turpeen alla Kuusivaaran eteläpuolisilla suoalueilla. Sora ja moreenien välinen hiekka esiintyy ylemmän hiekkamoreenin alla rajatuilla alueilla Kuusivaarassa, ja alempi hiekkamoreeni esiintyy useimmilla noista alueista lajittuneiden sedimenttien alla. Silttimoreenia esiintyy vain Kuusivaaran eteläpuolella, laajimmin turvealueilla muiden sedimenttiyksiköiden peittämänä. Pre-glasiaalinen rapakallio on yleistä Kuusivaarassa, mutta rapakalliota ja kalliota ei pystytty erottamaan luotettavasti toisistaan 3D-mallissa.

Pintahiekka ja ylempi hiekkamoreeni arvioitiin mallin potentiaalisimmiksi yksiköiksi, joista voitaisiin kaivaa maa-ainesta raaka-aineeksi. Potentiaalisesti kaivettaviksi pintahiekan massoiksi arvioitiin n. 300 000 t Kuusivaaran länsiosassa < 50 cm pintakerroksena ja n. 37 000 t Pinoharjulla < 30 cm pintakerroksena. Potentiaalisesti kaivettaviksi ylemmän hiekkamoreenin massoiksi Kuusivaarassa arvioitiin n. 26 000 000 t ilman, että yksikön fysikaalisten ominaisuuksien vaihtelua otettiin huomioon.

Sedimenttien geokemiallisten analyysien tulokset osoittavat, että raskasmetallipitoisuudet sedimenttinäytteiden raekokofraktiossa < 2 mm ovat n. 50 – 65 % verrattuna pitoisuuksiin raekokofraktiossa < 0.06 mm. Kahta näytepopulaatiota, kaikkia sedimenttinäytteitä yhdistettynä ja ylemmän hiekkamoreenin näytteitä, verrattiin Valtioneuvoston asetuksen maaperän pilaantuneisuudesta ja puhdistustarpeen arvioinnista kynnysarvoihin sekä kromin ja nikkelin suurimpiin suositeltuihin taustapitoisuuksiin Kuusivaarassa. Raskasmetallipitoisuudet ovat yleisesti molemmissa näytepopulaatioissa raja-arvojen alapuolella, mutta korkeampia pitoisuuksia esiintyy yksittäisissä näytteissä. Metallien ja muiden yhdisteiden liukoisuudet näytteistä ovat alhaisia.

Ylemmän hiekkamoreenin vedenläpäisevyydeksi arvioitiin 10^{-6} – 10^{-4} m/s, arvojen ollessa korkeampia alueilla, joilla yksikkö on huuhtoutunut ja karkeampi. Rapakallion vedenläpäisevyydeksi arvioitiin n. 10^{-6} – 10^{-5} m/s. Vähäinen määrä rakeisuusnäytteitä muista 3D-mallin yksiköistä tuotti vedenläpäisevyyksiä, jotka olivat kyseisille sedimenttifasieksille kirjallisuudessa kuvatuilla vaihteluväleillä.

Muita tietoja

Asiasanat: kvartäärigeologia, 3D-malli, geokemia, vedenläpäisevyys, Kuusivaara, Sakatti, Sodankylä

UNIVERSITY OF OULU
Faculty of Technology

Abstract for thesis

Department	Degree Programme
Oulu Mining School	Degree Programme in Geosciences
Author	**Thesis Supervisor (of the university)**
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Title of Thesis			
A 3D geological model and geochemical and hydrogeological properties of sediments in Kuusivaara, Sodankylä, Finland			
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Abstract

Kuusivaara in Sodankylä, Finland, is the planned site for mining infrastructure for the Sakatti Cu-Ni-PGE mine project by Anglo American plc, and knowledge of the Quaternary sediments in Kuusivaara is needed for the design and planning of the infrastructure. The aim of this thesis was to construct a 3D model of the Quaternary sediments in the Kuusivaara area to define the spatial distribution of the different sediment units within the area. The geochemical and hydrogeological properties of the sediments were also studied.

The sedimentological data used in this study was obtained from test pits, soil drilling and peat coring logs, and ground penetrating radar profiles. A 3D model was created in the Leapfrog Geo software using the sedimentological data. The geochemistry of the sediments was studied with element analyses using aqua regia solution performed on recent sediment samples and archived till samples from 1973 and 1975. The solubility of metals and other substances was tested on a small number of samples using the two-step batch leaching test. The water permeability of the sediments was determined by slug tests in groundwater wells and by using empirical equations to estimate the water permeability based on the grain-size distributions of the sediment samples.

The created 3D model consists of a framework stratigraphy with nine units developed for the study area based on the *in situ* sedimentological data. The units in the stratigraphy are, listed from the top: peat, surface sand, upper sandy till, gravel, inter-till sand, lower sandy till, silty till, weathered bedrock, and bedrock. In the 3D model, the upper sandy till is widely the only sediment unit overlying the weathered bedrock and bedrock in Kuusivaara. The surface sand is present on the ground surface in limited areas and widely present below the peat on the mire areas south of the Kuusivaara hill. The gravel and inter-till sand are found below the upper sandy till in limited areas, and the lower sandy till is found in most of those areas below the sorted sediments. The silty till is found only south of the Kuusivaara hill, most widely in the wetlands overlain by other sediment units. Pre-glacial weathered bedrock is common in Kuusivaara, but weathered bedrock and bedrock were not discerned reliably in the 3D model.

The surface sand and upper sandy till units are estimated to be the most potential sediment units in the model for excavation as a raw material. The potentially excavatable surface sand masses are estimated at approx. 300 000 t as a < 50 cm surface cover in the western part of the Kuusivaara hill and at approx. 37 000 t as a < 30 cm surface cover in Pinoharju. The potentially excavatable upper sandy till masses in Kuusivaara are estimated at approx. 26 000 000 t without considering the variations in the physical properties of the unit.

The geochemical analysis results show that the heavy metal concentrations of the sediment samples in the grain-size fraction < 2 mm are approx. 50 – 65 % of the concentrations in the grain-size fraction < 0.06 mm. Two sample populations, all sediment samples combined and samples from the upper sandy till, were compared to the threshold limits in the Government Decree on the Assessment of Soil Contamination and Remediation Needs and the recommended background concentrations for chromium and nickel in Kuusivaara. Generally, the heavy metal concentrations are considerably below the limits in both sample populations, but higher concentrations are found in individual samples. The solubilities of metals and other substances from the samples are low.

The water permeability of the upper sandy till is estimated at $10^{-6} – 10^{-4}$ m/s, with higher values where the unit is washed and coarser. The water permeability of the weathered bedrock is estimated at $10^{-6} – 10^{-5}$ m/s. A few grain-size distribution samples from the other units of the 3D model produced water permeabilities within ranges reported for those sediment facies in literature.

Additional Information

Keywords: Quaternary geology, 3D model, geochemistry, water permeability, Kuusivaara, Sakatti, Sodankylä

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1 Introduction

A UK-listed global mining company 'Anglo American plc' made the discovery of a Cu-Ni-PGE deposit in Sodankylä, Finland, in 2009, and according to the present estimation, the deposit, later named Sakatti, is a significant mineralisation both in grade and tonnage (Brownscombe *et al*., 2015; Anglo American, 2020). Since 2009, the project has advanced from the exploration phase into a pre-feasibility study of an underground mine. At the moment, the project is in the permitting phase.

A wide range of aspects have been studied in the project to evaluate the exploitation of the ore deposit. These include, but are not limited to, ore geology, metallurgy, hydrogeology, mineral processing and biology. The environmental impact assessment (EIA) programme plan of the intended mine was delivered to the authorities in 2018 (Pöyry Finland Oy, 2018) and the completed EIA report was submitted to the authorities in November 2020 (FCG Suunnittelu ja tekniikka Oy, 2020).

The EIA includes three main alternatives for the design of the mine and its infrastructure (FCG Suunnittelu ja tekniikka Oy, 2020). All those alternatives host the processing facilities and infrastructure of the mine site on the Kuusivaara hill, approximately four kilometres south of the ore deposit and approx. 12 kilometres north of the town of Sodankylä. The infrastructure planned to be built in Kuusivaara includes, for example, the mineral processing plant, tailings and waste rock storage facilities, and roads. Kuusivaara is also the most preferred area to build the tunnel entrance to the underground mine.

The Quaternary sediments overlaying the bedrock in the infrastructure area will be largely removed when the construction of the infrastructure starts. The excavated sediments will be partly used as building material for the infrastructure and the rest of the material will be stored and used later for landscaping of the area during the closure phase of the mine site. The sediment cover in the Kuusivaara area is known through public geological and topographical data, drilling data by AA Sakatti Mining Oy, and data from test pits previously excavated in the area. However, these data sets do not entirely cover the area of interest. In addition, the data sets do not provide a sufficient amount of information on the geochemistry of the Quaternary overburden in the area.

The knowledge of the geochemical properties of the sediment cover is crucial, since there are specific requirements and limitations for using the sediments for infrastructure construction and landscaping set in legislation (e.g. Government Decree on the Assessment of Soil

Contamination and Remediation Needs, 214/2007). Thus, a reliable database of the stratigraphy, geochemical and geotechnical characteristics of the sediments is needed, in order to evaluate the volumes and tonnages of the different types of sediments in Kuusivaara. The most natural choice as the database format is a 3D model of the Quaternary sediments that can record the spatial variations in the Quaternary sediment cover accurately. Furthermore, the geochemical and other properties of the sediment cover can be linked to the modelled sediment units.

The purpose of this study was to collect data on the Quaternary sediments of the Kuusivaara area to supplement the pre-existing data sets, and to construct a 3D model of the sediments to provide a tool for the planning of the mine infrastructure site. In addition, the geochemistry of the sediment units in the model was compared to the legal framework for sediments to estimate the amounts of material suitable for different purposes in the future. Regarding the geotechnical properties of the sediments, water permeabilities were estimated for the units of the 3D model. The study area of approx. 9 km^2 is situated in the municipality of Sodankylä in northern Finland (Figure 1).

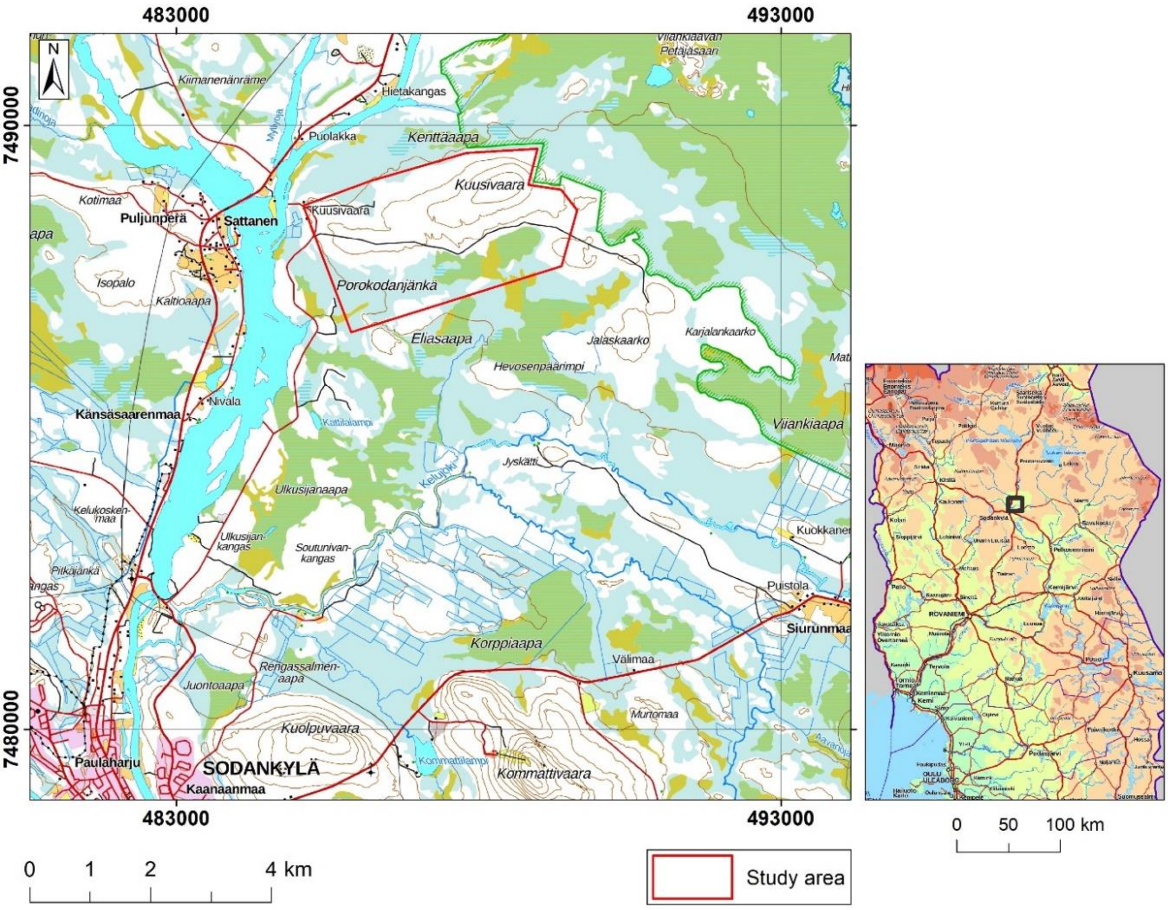

Figure 1: The study area of this thesis in Kuusivaara, Sodankylä, Finland. Background maps by National Land Survey of Finland.

2 Regional geology

2.1 Bedrock geology

The bedrock of northern Finland is part of the Fennoscandian Shield (Hanski & Huhma, 2005), and the regional geology in Central Lapland consists of several Paleoproterozoic and Archean lithological units (Vaasjoki *et al*., 2005; Geological Survey of Finland (GTK), 2019a) (Figure 2).

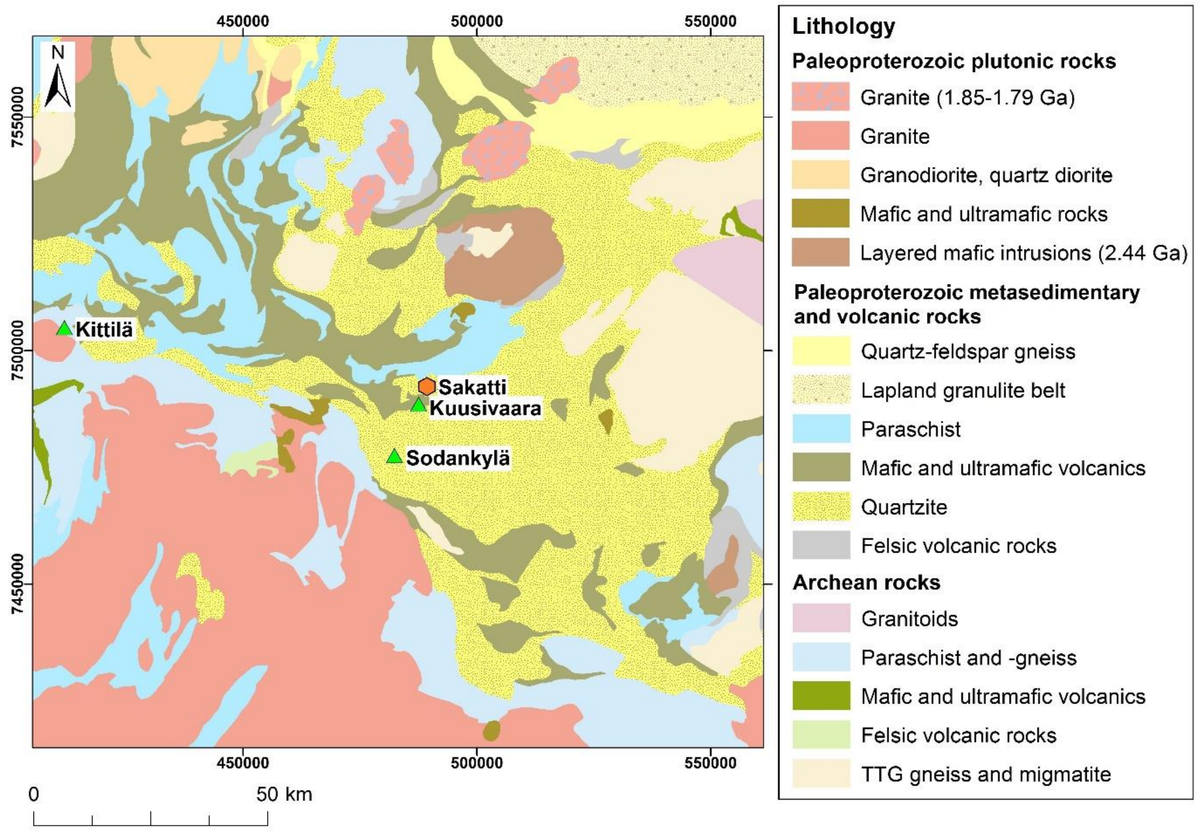

Figure 2: The main lithological units in the region according to the bedrock map, scale 1:5 000 000 (GTK, 2019a).

Kuusivaara is located within the Central Lapland Greenstone Belt (CLGB). The large-scale bedrock geology of the area consists of the following main units: the Koitelainen and Kevitsa mafic intrusions approx. 30 km to the north (of Kuusivaara), the Lapland Granulite Belt approx. 80 km to the northeast, Archean gneisses, migmatite and granitoids approx. 50 km to the east, the Central Lapland Granitoid Complex approx. 25 km to the southwest, and various metasedimentary and volcanic rocks of the CLGB to the northwest and southeast (Hanski & Huhma, 2005; GTK, 2019a).

The Kuusivaara hill consists mainly of picritic volcanic rocks (GTK, 2017) (Figure 3). Towards the north from Kuusivaara, the bedrock consists of a narrow zone of siltstone, mafic volcanic rocks, quartzites, siltstones, gabbros, graphite paraschists and mafic tuffs. Towards the south from Kuusivaara, the bedrock consists of graphite paraschists, quartzites, dolerites, siltstones and biotite paragneisses. The bedrock in the area west of Kuusivaara is composed of picritic volcanic rocks, siltstones, mafic volcanic rocks, graphite paraschists, quartzites and komatites. East of Kuusivaara, the bedrock consists of quartzites, graphite paraschists, biotite paragneisses and diorites.

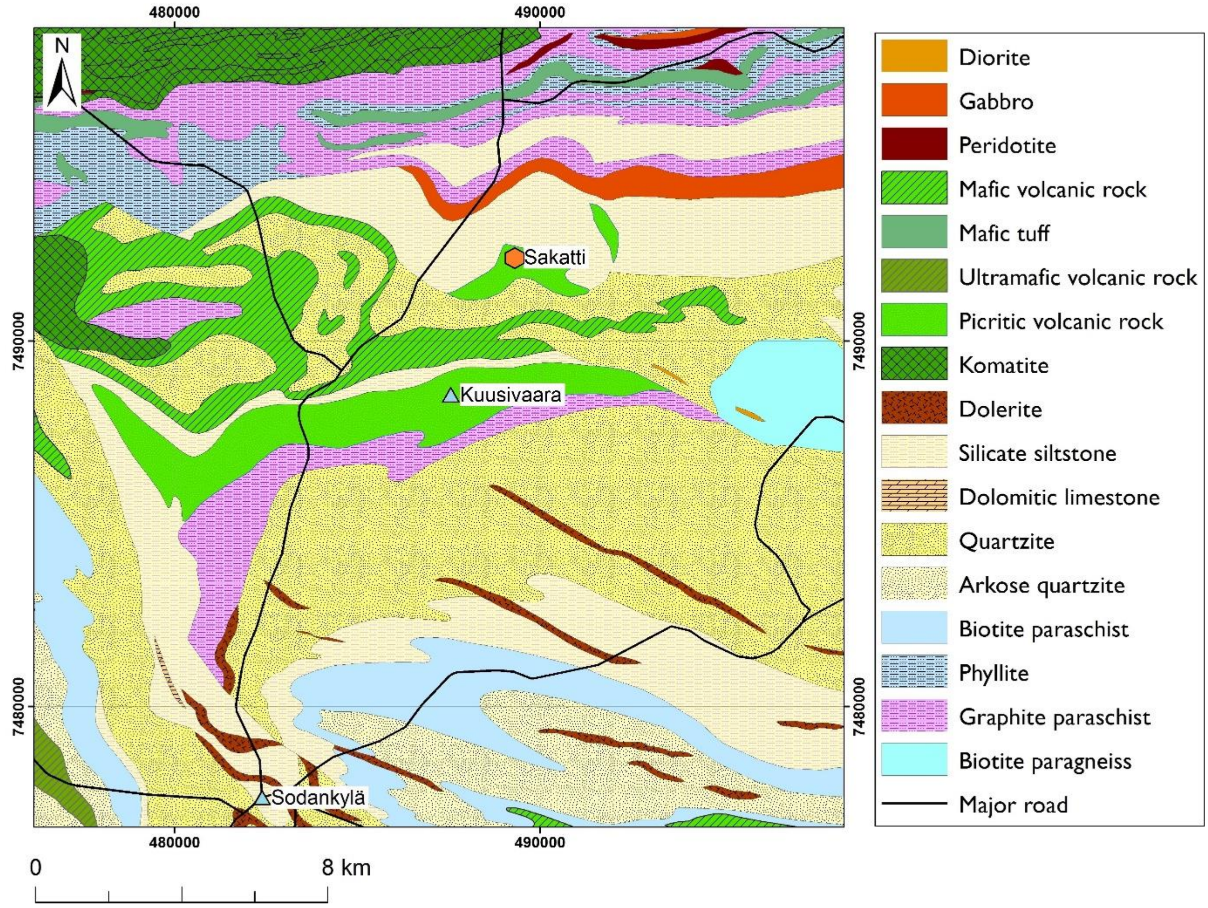

Figure 3: The bedrock geology around the study area according to the bedrock map, scale 1:200 000 (GTK, 2017).

The bedrock in the ice divide zone of Central Lapland (Figure 4) is often weathered (Hirvas, 1991; Hall *et al*., 2015). The Sodankylä municipality, including Kuusivaara, is located in this pre-glacially weathered bedrock area. The uppermost part (10 – 20 m) of the bedrock is weathered to varying degrees and can be described as saprolite (Nenonen *et al*., 2018). This pre-glacial bedrock weathering formed most likely during the Neogene (Nenonen *et al*., 2018).

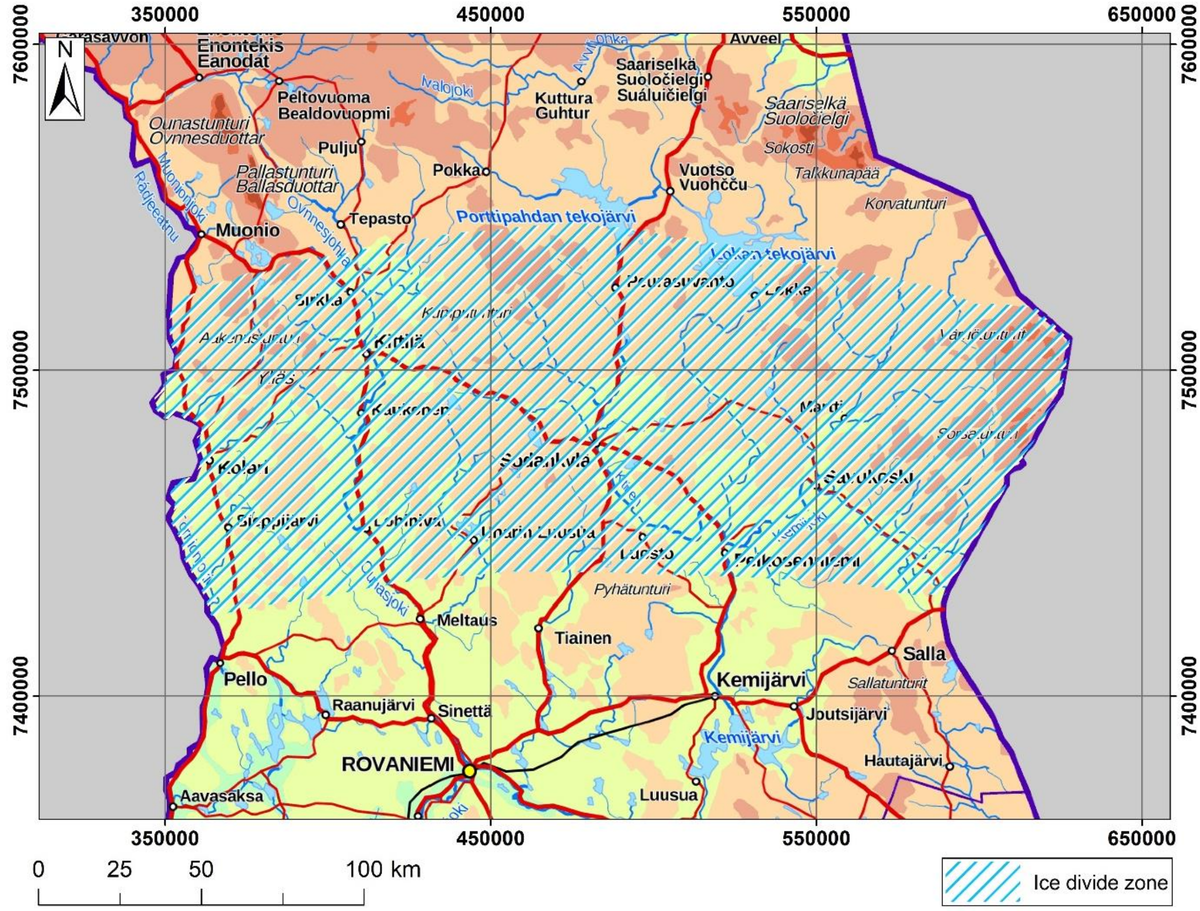

Figure 4: Ice divide zone of the last glaciation in Central Lapland as described by Hirvas (1991). Background map by National Land Survey of Finland.

2.2 Quaternary geology

Hirvas (1991) established the till stratigraphy of Finnish Lapland based on approx. 1400 test pits excavated during a research project carried out between 1972 and 1977 (Hirvas *et al*., 1977). Additional test pit investigations in Finnish Lapland were conducted between 1977 and 1989 to gain further knowledge on the till stratigraphy of northern Finland (Hirvas, 1991). During the time Hirvas *et al*. (1977) and Hirvas (1991) carried out stratigraphical investigations in Lapland, the only reliable absolute dating method was radiocarbon (C-14) dating. Therefore, only C-14 ages less than 40 000 years before present (BP) were possible to date accurately and the dated material yielding ages more than c. 40 000 years BP could only be interpreted as minimum ages (Hirvas, 1991).

Hirvas (1991) described six till beds corresponding to six ice flow or glaciation stages over Finnish Lapland. The till beds representing the ice flow stages were numbered from the youngest to the oldest I-VI. In his description, he also included a till unit called 'surficial till', which referred to any topmost till layer that was on top of the till bed II, but not a basal till (i.e. till bed I).

The description below refers to Hirvas (1991) and it focuses on his description regarding the ice divide zone in particular. The zone was defined as the area where the till clast fabric in the till units changed drastically even in adjacent test pits, hence implying drastic changes also in the ice flow directions.

The youngest till unit in Lapland, the so-called till bed I, was observed in 50 of the studied approx. 1400 sites. Till bed I is on average 1.3 m thick, massive till with a fine sand matrix showing some fissility and a strong till clast fabric. Till clast fabric measurements from the Central Lapland sites indicate an ice flow direction ranging from the northwest to the southeast and from the west to the east. Till bed I was most likely deposited during local ice oscillations at the final stages of the last deglaciation.

Till bed II, representing ice flow stage II, is widespread over Finnish Lapland and was found in 80 % of the test pits and drill holes studied in Central Lapland (Hirvas, 1991). This till bed is most often the topmost till in Finnish Lapland and at only nine sites out of approx. 1400 some other till bed was the topmost till bed in sections (Hirvas *et al*., 1977). The till is on average 1.9 m thick, has a sand matrix, it is often stratified, and contains abundant weathered bedrock fragments particularly in the ice divide zone. The till clast fabric in till bed II is not strong but scattered and shows no preferred or statistically significant clast orientation. Hirvas (1991) considered that till bed II was deposited during the last deglaciation.

Till bed III was observed in 212 of the studied approx. 1400 sites. The thickness of the till bed varies between 0.5 m and > 6 m, and the bottom of the till bed was reached in only 19 % of the sites. The till is compact and has a (commonly blueish grey) fine sand matrix that is either massive or shows fissility. Both the upper and lower contact of till bed III are usually distinct erosional contacts. The till clast fabric in till bed III shows a strong clast orientation from northwest to southeast. Hirvas (1991) considered that till bed III was deposited during the ice flow stage III when the ice divide zone was situated approx. 50 – 100 km north of the ice divide zone of the latest glaciation.

Older till beds than till bed III were observed in 17 test pits, but Hirvas (1991) used the names till bed IV-VI only locally at the Rautuvaara and Naakenavaara sites. The thicknesses of the older till beds vary between 1 m and 6.4 m. The tills are compact, and the upper parts of the till beds usually contain boulders. The upper contacts of the older till beds are usually distinct. The correlation of the older till beds IV-VI across Lapland was not possible since the data was too scarce to establish a firm correlation of the till beds. Most of the test pits, in which the older till beds were encountered, were located in the Late Weichselian ice divide zone and in the area with pre-glacial weathered bedrock.

Hirvas (1991) correlated the till beds I – VI across Finnish Lapland with the aid of biostratigraphical results obtained from organic-rich sediments, which were interbedded with the till units. His data included 49 sites, mostly situated in the ice divide zone, where organic deposits were interbedded with tills. Based on this data, Hirvas (1991) considered the till beds I – III were deposited during three Weichselian glacial events: the till beds I – II during the Middle-Late Weichselian glaciation and the till bed III during the Early Weichselian glaciation. Till bed IV was considered to have been deposited during the Saalian glaciation and the older till beds during the pre-Holsteinian glacial events. Till beds V – VI were best represented in the Rautuvaara open pit and Hirvas (1991) suggested that they represented pre-Holsteinian, possibly Elsterian, tills with the time interval between the beds V and VI being unknown.

The descriptions given by Hirvas (1991), regarding the separate till beds, are still regarded as valid, but some aspects of the chronostratigraphy he presented have been challenged. Hirvas' (1991) interpretation that the Naakenavaara peat unit was deposited during the Holstein interglacial and the till bed beneath the peat unit was laid down during the Elsterian glaciation is plausible, but further evidence is needed to confirm this (Johansson *et al*., 2011). Hirvas (1991) interpreted the till beds V-VI in the Rautuvaara open pit to represent pre-Holsteinian tills, but more recent studies in the Rautuvaara open pit, including sands which have been dated with Optically Stimulated Luminescence (OSL) in between the till units, indicate that all the till beds observed in Rautuvaara (till beds III-VI) were deposited during different stages of the Weichselian glaciations (Lunkka *et al*., 2015).

The interpretation that the Tepsankumpu and Paloseljänoja interglacial sediments correlate with the Eemian interglacial is generally considered to be valid and therefore till bed IV must have been deposited during the Saalian glaciation (Johansson *et al*., 2011). In addition, it is also generally accepted that till beds I – III were most likely deposited during the Weichselian stage. Some studies have suggested that the organic deposits interpreted as Weichselian interstadial deposits could have been transported during a glaciation and actually formed during the Eemian interglacial (Punkari & Forsström, 1995; Forsström & Punkari, 1997). Thus, Lapland together with most of Fennoscandia would have been continuously covered by an ice sheet between the

Eemian interglacial and the last, Late-Weichselian, deglaciation. Studies supporting two or three separate Weichselian ice sheet advances have been, nevertheless, more numerous and it is the prevalent view in literature (e.g. Helmens *et al*., 2000; Sarala, 2005; Helmens *et al*., 2007; Johansson *et al*., 2011).

3 Quaternary geology of the Kuusivaara area

The Quaternary superficial deposits map of Sodankylä in the scale 1:20 000 (Sarala *et al*., 2015; GTK, 2018) shows that Kuusivaara is a till-covered hill except for a narrow zone of sand on its western flank, a small area of sand on the northeastern edge and small bedrock outcrops on the higher parts of the hill (Figure 5). Several ancient drainage channels are mapped on the southern slope of Kuusivaara. The mire areas around Kuusivaara are covered with peat (*Carex*) except for the small, forest-covered ridges which are till-covered.

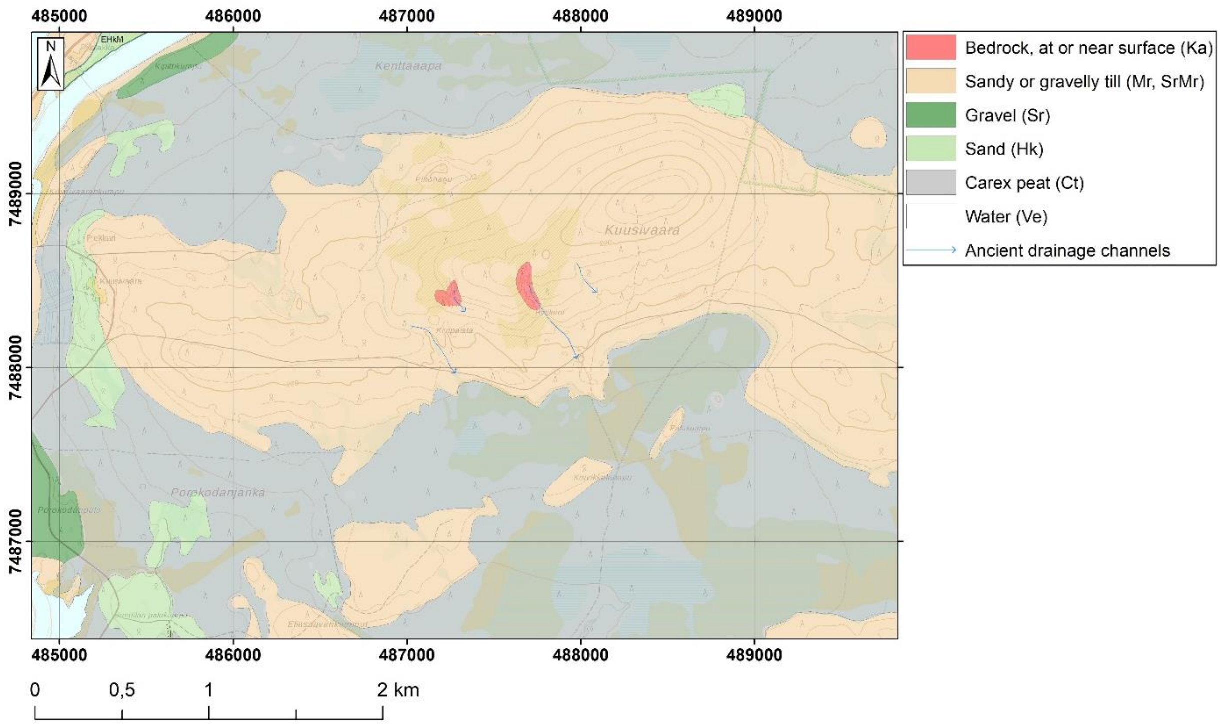

Figure 5: Base sediments (depth 1 m) in Kuusivaara on the Quaternary superficial deposits map of Sodankylä in scale 1:20 000 (GTK, 2018).

A hillshade image of the Kuusivaara area created with the elevation model by National Land Survey of Finland (NLS) (2020) reveals some aspects of the Quaternary geology of the Kuusivaara hill (Figure 6). The northwestern parts of the hill show signs of surface water flow either as part of a lake (lake terraces) or floods of the River Kitinen (area A in Figure 6). Possible lateral drainage channels are visible on the northern slope of the Kuusivaara hill (area B in

Figure 6). Pinoharju hill can be seen as a distinct, elevated formation on the northern slope of the Kuusivaara hill. The southern slope of Kuusivaara shows several melt-water drainage channels, which were also present on the surficial deposits map. The area south from the drainage channels shows signs of mass-flows and one deltaic structure that extends on to the mire (area C in Figure 6). Bedrock structures are visible on the eastern parts of the southern slope, in addition to places on the eastern and northeastern slopes (area D in Figure 6).

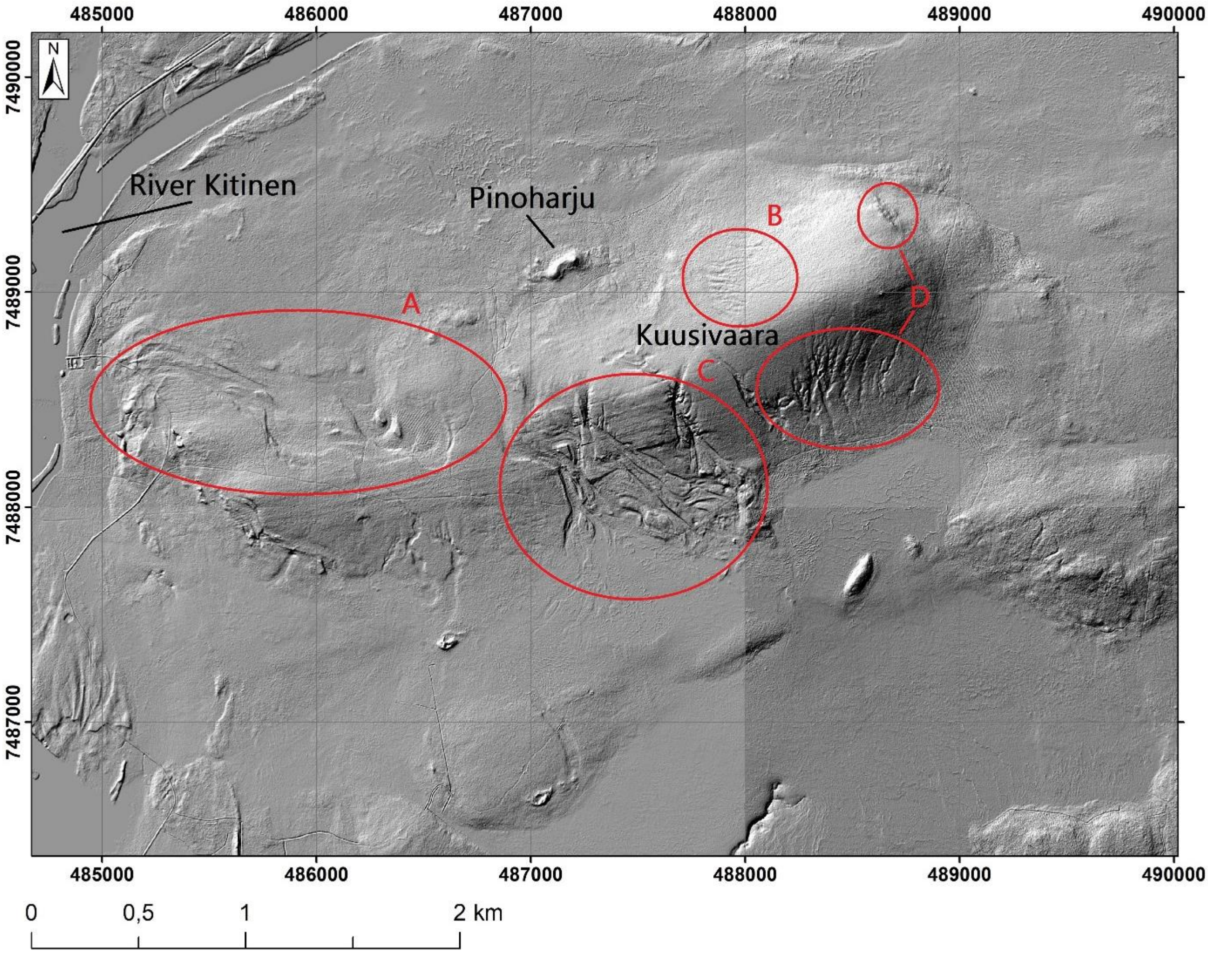

Figure 6: A hillshade image of the Kuusivaara area (NLS, 2020). The marked areas: signs of surface water flow as part of a lake or floods of the River Kitinen (A), possible lateral drainage channels (B), drainage channels and signs of mass-flows (C), and bedrock structures (D).

The area surrounding Kuusivaara was under the Moskujärvi ice lake, which covered an area of 400 km^2, between c. 10 400 and 10 300 years ago (Johansson, 2005; Johansson & Kujansuu, 2005). Its level was first at approx. 207 m above sea level (a.s.l.) when it drained towards the east to the valley of the River Luiro (Johansson, 2005). Later, the water level lowered to approx. 195 m a.s.l. when the ice lake drained through the Hirviäkuru gorge towards the southeast. The ice sheet retreated from the Kuusivaara area c. 10 300 years ago (Johansson & Kujansuu, 2005) and as the River Kitinen valley was deglaciated, the Ancylus Lake covered the area. The highest

Ancylus Lake water level in the area reached approx. 186 m a.s.l. at that time (Johansson, 2005). The formation of mires in the Sodankylä area began after the deglaciation c. 9800 – 10200 years ago (Mäkilä *et al*., 2013).

Salonen *et al*. (2018) studied the Kuusivaara area and excavated six test pits on the southern flank of Kuusivaara. Their results indicate that till makes up most of the overburden in the area and that there are two superimposed till units. The lower till is compact with a fine matrix and the upper till is loose with a sand matrix. The till thicknesses in their test pits varied between 2 – 5 m. Sorted sediments were also observed between the till beds in some of the test pits.

Two till beds, the till beds II and III of Hirvas (1991), occur in the Kevitsa area approx. 20 km north of Kuusivaara (Hirvas *et al*., 1994). In that area, the lower till bed III is compact and contains lots of large clasts, whereas the upper till bed II is loose and contains, on average, smaller clasts. The contact between the till beds is distinct and there is often a boulder-rich layer between the tills.

Based on the previous descriptions (Hirvas, 1991; Hirvas *et al*., 1994; Salonen *et al*., 2018), it is likely that the Kuusivaara area contains the till beds II and III of Hirvas (1991). Till bed IV has been encountered in some test pits in the Sodankylä municipality, but studies at or adjacent to Kuusivaara did not encounter the till bed IV. The till beds II and III were most likely deposited during the Late-Weichselian and Early- to Middle-Weichselian stages, respectively. At and around the Kuusivaara area, the till clast fabrics of the till beds II and III indicate that the ice flow directions during their deposition were from the northwest to the southeast and from the west-northwest to the east-southeast, respectively. However, as Kuusivaara is situated in the close vicinity of the last ice divide zone, the till clast fabrics in the area can vary significantly even locally.

A sedimentary 3D model has been constructed for an area on the western edge of Viiankiaapa, approx. 3 km north of Kuusivaara (Åberg *et al*., 2017; Åberg *et al*., 2021, submitted). The modelled area contains peat-covered parts of the Viiankiaapa mire and mineral soil-covered land west of the mire on both sides of the River Kitinen. The datasets used to build the model included primarily test pit observations and ground penetrating radar and drilling data. The model contains a peat layer, three till layers, four sorted sediment layers, a weathered bedrock layer and a bedrock layer.

The geochemistry of the surficial sediments in the area surrounding the Sakatti mineral deposit, including Kuusivaara, was studied by GTK in 2017 (GTK, 2020). A total amount of 63 samples were taken and of those 32 were surface samples (depth 0 – 25 cm) and 31 deeper samples (70 – 110 cm). The soil types of the samples were: 25 till samples, 32 sand or gravel samples, and 6 fine samples. The samples were sieved below 2 mm and chemical compositions were determined in aqua regia solution.

The results were reported for the 11 metals and half-metals listed in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007). The results show that the concentrations of the studied elements in the area surrounding the Sakatti mineral deposit are relatively low (Table 1). Recommended background concentration values were calculated for all the reported elements based on the results, and the calculated values for two elements, chromium (Cr) and nickel (Ni), exceed the threshold value set in the government decree. The maximum concentrations measured in individual samples exceed the threshold value for three elements: arsenic (As), Cr and Ni.

Table 1: The geochemical concentrations of the surficial sediments (n = 63) in the area surrounding the Sakatti mineral deposit, including Kuusivaara (GTK, 2020). The recommended background concentration value field is left empty for elements, whose calculated background concentration value is below the threshold value set in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007).

Element	Median value [mg/kg]	Maximum value [mg/kg]	Threshold value [mg/kg]	Recommended background concentration value [mg/kg]
Antimony (Sb)	0.04	0.22	2	
Arsenic (As)	1.53	7.0	5	
Mercury (Hg)	0.009	0.025	0.5	
Cadmium (Cd)	0.02	0.06	1	
Cobalt (Co)	6.9	19.3	20	
Chromium (Cr)	76.1	367	100	162
Copper (Cu)	16.2	72.3	100	
Lead (Pb)	2.2	7.1	60	
Nickel (Ni)	28.2	151	50	61
Vanadium (V)	44.2	95.3	100	
Zinc (Zn)	15.0	44.0	200	

4 Legal framework for sediments as a raw material

Extractable Land Resources Act (555/1981) governs the excavation of sediments in Finland and aims for environmentally sustainable extraction of land resources. The scope of the law is "extraction of rock, gravel, sand, clay and soil to be transferred away or to be stored in place or to be refined" (555/1981). However, there are three exceptions of sediment extraction, which are not subject to the Extractable Land Resources Act: excavation of sediments based on the Mining Act (621/2011), excavation and use of sediments in connection with construction if the construction has been granted a permit or the construction plans have been approved by authorities, and such extraction of sediments in waters that requires a permit from the Regional State Administrative Agency as described in the Waters Act (587/2011). In the case of Kuusivaara, the possible future use of sediments will most likely fall under either of the first two exceptions and is in such a case not subject to the Extractable Land Resources Act.

According to the Waste Law (646/2011) and a memorandum given by the Ministry of Environment (2015), excavated sediments are not classified as waste if the following criteria are met:

1. **The concentrations of harmful substances in the sediments do not damage or cause danger to environment.** This is commonly defined so that the concentrations need to be either lower than the threshold value in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007) or lower than the background concentration in the usage area. Background concentration is defined as the concentration in sediments that is either the natural concentration or wide-spread anthropogenic concentration from several sources (e.g. old industrial areas).
2. **The sediments are certainly used in the future.** This is indicated, for example, by transferring the excavated sediments directly to the location of use without long-term storage. Storage is usually deemed long-term if it lasts more than a year and is not specified as part of construction plans.
3. **The use of the sediments is planned.** An estimate of the amount of sediments needed, time of use, a proven need for the sediments, and a technical description of the use should be presented in the planning. The planned use is often presented, for example, in the construction permit or waste management plans.
4. **The sediments can be used without further processing.** Pre-treatment with mechanical means, such as sorting, mixing or crushing, is not considered further

processing in these criteria. The same is also true for other methods, which aim only to improve the construction properties of the sediments (e.g. stabilizing fine sediments).

Furthermore, Ministry of Environment (2015) has clarified that sediments, which are not considered waste (i.e. they fill the criteria above), are not subject to the Waste Law (646/2011). However, there can be other requirements for sediments which are not considered waste, such as technical requirements set for road and infrastructure materials.

In this thesis, the most relevant of the four criteria listed above is the first one concerning the concentrations of harmful substances in the sediments. The Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007) lists 12 inorganic and 41 organic substances as the most common harmful substances in sediments and gives concentration limits for each of those. All the organic substances listed are anthropogenic and as Kuusivaara has not been subject to any industrial activity, it is very unlikely that the sediments would be contaminated with the listed organic substances. Additionally, one of the inorganic substances, cyanide, can be dismissed based on the same reasoning.

Thus, the relevant substances to consider in Kuusivaara are the 11 metals and half-metals listed in the decree: antimony (Sb), arsenic (As), mercury (Hg), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), zinc (Zn) and vanadium (V). The decree (214/2007) lists three concentration limits for each of these elements: a threshold value, a lower guideline value and a higher guideline value (Table 2). The possible contamination and remediation need to be assessed if the concentration of one or more of the elements in the sediments exceeds the threshold value given in the decree or exceeds the background concentration in case the threshold value is lower than the background concentration. The sediments are usually considered contaminated if the higher guideline value of one or more elements is exceeded in an industrial, storage, traffic or similar area. In all other areas, the sediments are usually considered contaminated if the lower guideline value of one or more elements is exceeded. The concentrations should be analysed from the fraction < 2 mm.

Table 2: The threshold value, lower guideline value and higher guideline value for the metals and half-metals listed in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007). The values in parentheses for chromium and nickel are the recommended background concentration values in the Kuusivaara area (GTK, 2020).

Element	Threshold value [mg/kg]	Lower guideline value [mg/kg]	Higher guideline value [mg/kg]
Antimony (Sb)	2	10	50
Arsenic (As)	5	50	100
Mercury (Hg)	0.5	2	5
Cadmium (Cd)	1	10	20
Cobalt (Co)	20	100	250
Chromium (Cr)	100 (162)	200	300
Copper (Cu)	100	150	200
Lead (Pb)	60	200	750
Nickel (Ni)	50 (61)	100	150
Zinc (Zn)	200	250	400
Vanadium (V)	100	150	250

The background concentration in the Kuusivaara area has been studied by GTK in 2017 (GTK, 2020). They reported that for two elements, Cr and Ni, the background concentration was higher than the threshold value. The recommended background concentration value for Cr was 162 mg/kg and for Ni 61 mg/kg (Table 1).

In the case of Kuusivaara, the legislation can be summarized from a geochemical point of view so that sediments, whose concentrations of harmful substances are below the threshold value or the recommended background concentration for chromium and nickel, can be used without any environmental permits (Ministry of Environment, 2015). Commercial or industrial usage of sediments, whose concentrations of harmful substances exceed the threshold value or the recommended background concentration for chromium and nickel, requires an environmental permit. In addition, those sediments need to be studied in more detail to determine if they are considered dangerous waste or other waste (Ministry of Environment, 2015, 2019).

The solubility of metals is also one attribute that needs to be studied if the sediments will be stored for a longer time period. When evaluating the waste properties of materials to be placed in landfills, the solubility of metals is one of the parameters that has been set limits for in the

Government Decree on changing the Government Decision on Landfills (202/2006). The limits are used to classify waste as eligible to be placed in landfills for either stable, regular (or non-reactive hazardous) or hazardous waste based on solubility tests performed with a liquid-to-solid ratio of 10. This decree does not concern uncontaminated sediments or regular waste created in extraction, enrichment or storage of mineral resources. Thus, the sediments in Kuusivaara might not be subject to this legislation if they are used in construction, but the limits set in the decree are commonly used also in investigations of sediment remediation needs and determining the environmental suitability of industrial by-products (Kuusela-Lahtinen *et al.*, 2012). For this reason, the solubility test results in this study are also compared to the limits set in the decree, which are shown in Table 3.

Table 3: The solubility limits set for stable, regular and hazardous waste in the Government Decree on changing the Government Decision on Landfills (202/2006). The comparable solubility measurements are to be analysed using a liquid-to-solid ratio of 10 and the limit values are given in mg/kg in dry material.

Element or parameter	Stable [mg/kg]	Regular [mg/kg]	Hazardous [mg/kg]
Arsenic (As)	0.5	2	25
Barium (Ba)	20	100	300
Cadmium (Cd)	0.04	1	5
Chromium total (Cr_{tot})	0.5	10	70
Copper (Cu)	2	50	100
Mercury (Hg)	0.01	0.2	2
Molybdenum (Mo)	0.5	10	30
Nickel (Ni)	0.4	10	40
Lead (Pb)	0.5	10	50
Antimony (Sb)	0.06	0.7	5
Selenium (Se)	0.1	0.5	7
Zinc (Zn)	4	50	200
Chloride (Cl^-)	800	15 000	25 000
Fluoride (F^-)	10	150	500
Sulphate (SO_4^{2-})	1000	20 000	50 000
Phenol index	1	-	-
Dissolved organic carbon (DOC)	500	800	1 000
Total dissolved solids (TDS)	4000	60 000	100 000

5 Methods and materials

5.1 Previous data

5.1.1 Test pits

A research group from Salonen Environment and the University of Helsinki excavated and studied six sedimentological test pits at Kuusivaara in September of 2017 (Salonen *et al*., 2018). The research report of Salonen *et al*. (2018) is not public, but the M.Sc. thesis of Valkama (2018) can be referenced for descriptions of the same test pits.

The test pits studied by the University of Helsinki (Figure 7) were examined and described regarding their texture (e.g. grain-size, fabric), sediment structures and structural features (e.g. contact types, unit thickness). Fifteen samples were collected from the test pits. Grain-size was determined from 14 samples in the laboratory using dry and wet sieving. The fine fraction was determined using a laser diffractometer and an aerometer. The age of one sample was determined utilising OSL dating.

Two till units were observed in the test pits as well as sorted sediment units both above and between the till beds. In those test pits, in which both till beds were observed superimposed, the lower till was compact, rich in fragments of weathered bedrock and showed a distinct reddish hue. The upper till was loose with a sand matrix. A thin sand layer (< 1 m) was observed between the two till beds. A sample from this sand layer was OSL-dated at 70 000 ± 14 000 years BP.

Sand and gravel beds with thicknesses of 0.25 – 5.2 m were observed in two test pits, which were located on the melt-water- and mass-flow-affected area on the southern slope of the Kuusivaara hill. A sand layer was also observed as the uppermost unit in one test pit in the western flank of Kuusivaara.

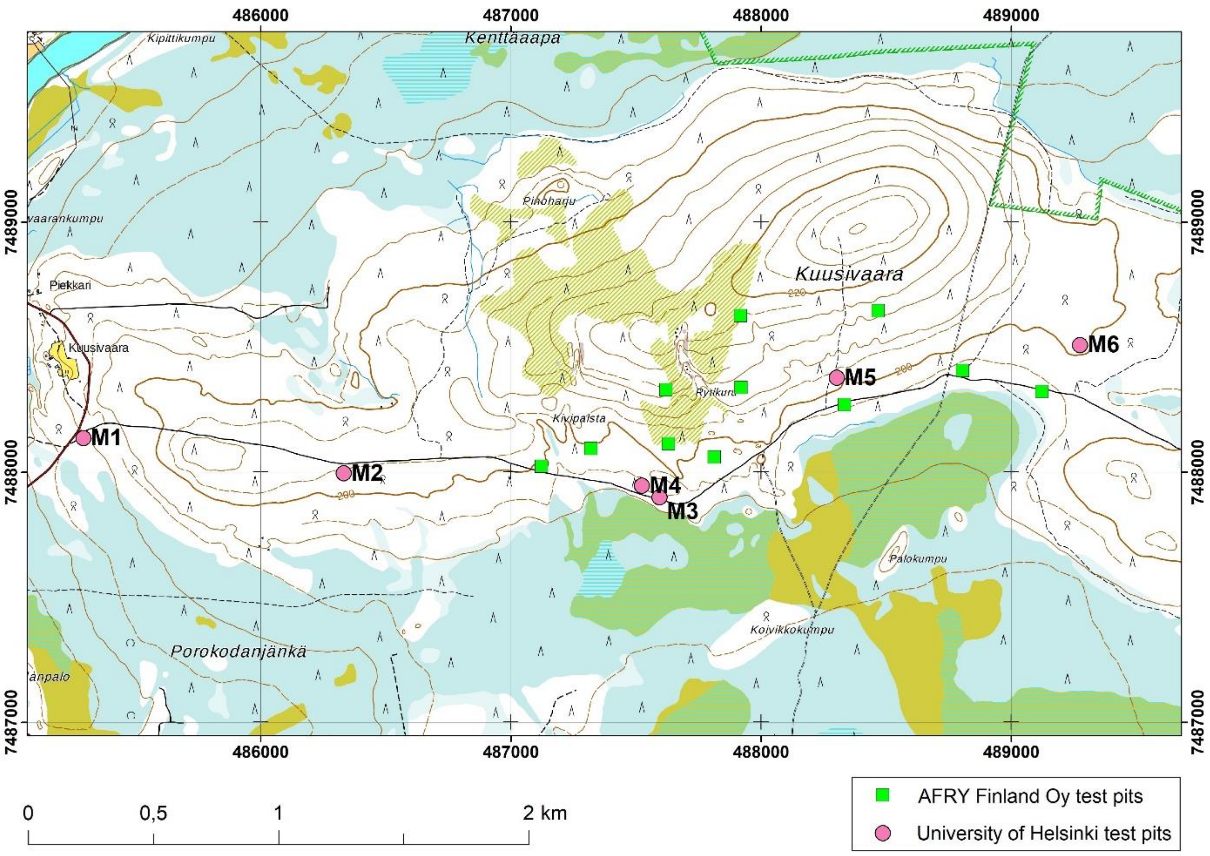

Figure 7: The locations of the test pits excavated by the University of Helsinki in 2017 and AFRY Finland Oy in 2020. Background map by National Land Survey of Finland.

AFRY Finland Oy excavated 11 geotechnical test pits in Kuusivaara in June 2020 on behalf of AA Sakatti Mining Oy. The programme aimed to investigate the sediments on the southern side of the hill from a geotechnical point of view. The test pits were dug with a tractor excavator to a depth of three metres or less if the bedrock surface was reached before that. Different soil types were identified on a visual basis and samples were taken with the excavator from each of the different soil layers to determine the grain-size distribution. A sedimentary log was recorded for each pit based on the field observations and the grain-size distribution analyses.

Only one of the test pits did not reach the bedrock surface at 3 m or less. That pit was terminated at 3 m with sandy till as the lowest sediment unit. The depth of the sediment cover was approx. 0.8 – 2.3 m on the upper parts of the southern slope of Kuusivaara and mostly 2 – 3 m at lower elevations. The lowest observed sediment unit was till in all of the pits and sorted sediments were observed in 8 of the 11 test pits.

5.1.2 Drilling data

Mitta Oy has drilled 8 shallow holes in the Kuusivaara area on behalf of AA Sakatti Mining Oy (Figure 8). The holes were drilled using rotary coring and disturbed sediment samples were acquired with one-metre intervals. The sediments in the holes were logged using the disturbed samples and later groundwater pipes were installed into the holes. The logs of these holes were used to provide supplementary information for the interpretation of ground penetrating radar profiles.

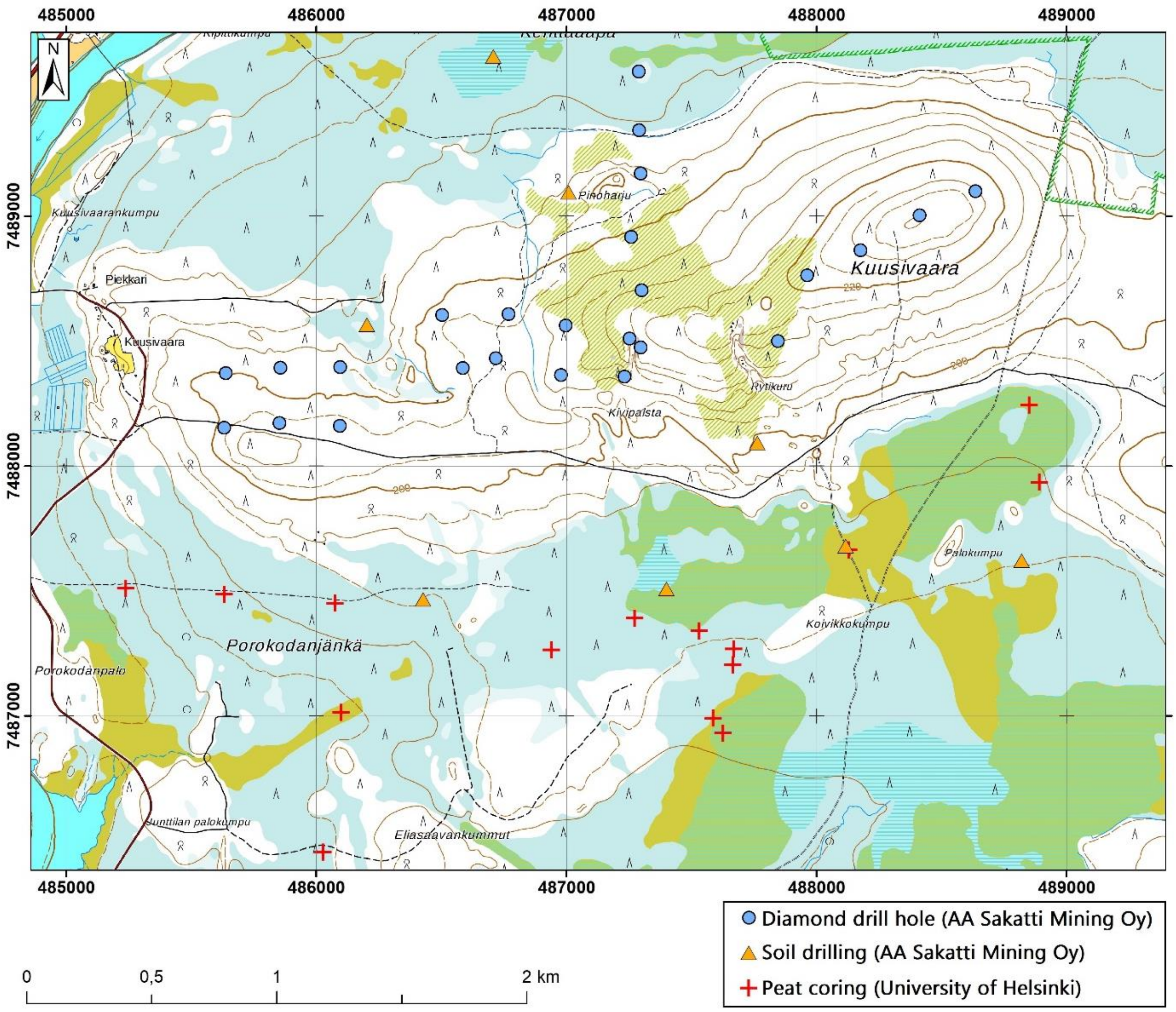

Figure 8: The locations of the diamond drill holes, soil drilling sites and peat coring sites, whose data were utilized in this study. Background map by National Land Survey of Finland.

Oy Kati Ab drilled 25 diamond drill holes in the Kuusivaara area on behalf of AA Sakatti Mining Oy. In the drill logs, the thickness of the sediment cover over the bedrock contact was recorded to the nearest 10 cm. The diamond drill holes are used in the 3D modelling to provide information on the depth of the bedrock surface. However, in diamond drilling a boulder above the actual bedrock surface can give an erroneous depth of the bedrock surface. Similarly, it could be sometimes difficult to distinguish whether the drilling is penetrating through the sediment cover or weathered bedrock. For these reasons, the bedrock surface depths recorded in diamond drilling were not used in the 3D modelling as an input data set, but only as an additional data set to confirm interpretations of the bedrock surface in the ground penetrating radar data.

The University of Helsinki carried out peat coring on the mires south of Kuusivaara at fifteen sites (Salonen *et al*., 2018; Valkama, 2018). As a part of their sedimentological studies, peat coring was performed with a 3 cm diameter manual corer and the peat thickness and the type of the underlying sediment were determined. The peat thickness varied between < 0.50 – 5.30 m. At nine out of the fifteen sites, the type of the underlying sediment was unclear, at four sites the underlying sediment was till, at one site the underlying sediment was sand and at one site the underlying sediment was silt. At the sites, where the sediment type was unclear, organic matter (gyttja) was mixed with the mineral soil.

5.1.3 Ground penetrating radar (GPR) data

AA Sakatti Mining Oy and the University of Helsinki performed approx. 100 km of GPR surveying in Kuusivaara in March, April and August of 2020 (Figure 9). The surveys were done in the winter on a thick snow cover using skis and in the summer on foot. Antenna frequencies 30 MHz, 50 MHz, 100 MHz and 250 MHz were used, but not all lines were surveyed using all four frequencies. Most profiles were surveyed with 50 and 100 MHz antennae, and the 250 MHz antenna was used on a few profiles. The profiles were tracked using time-triggering.

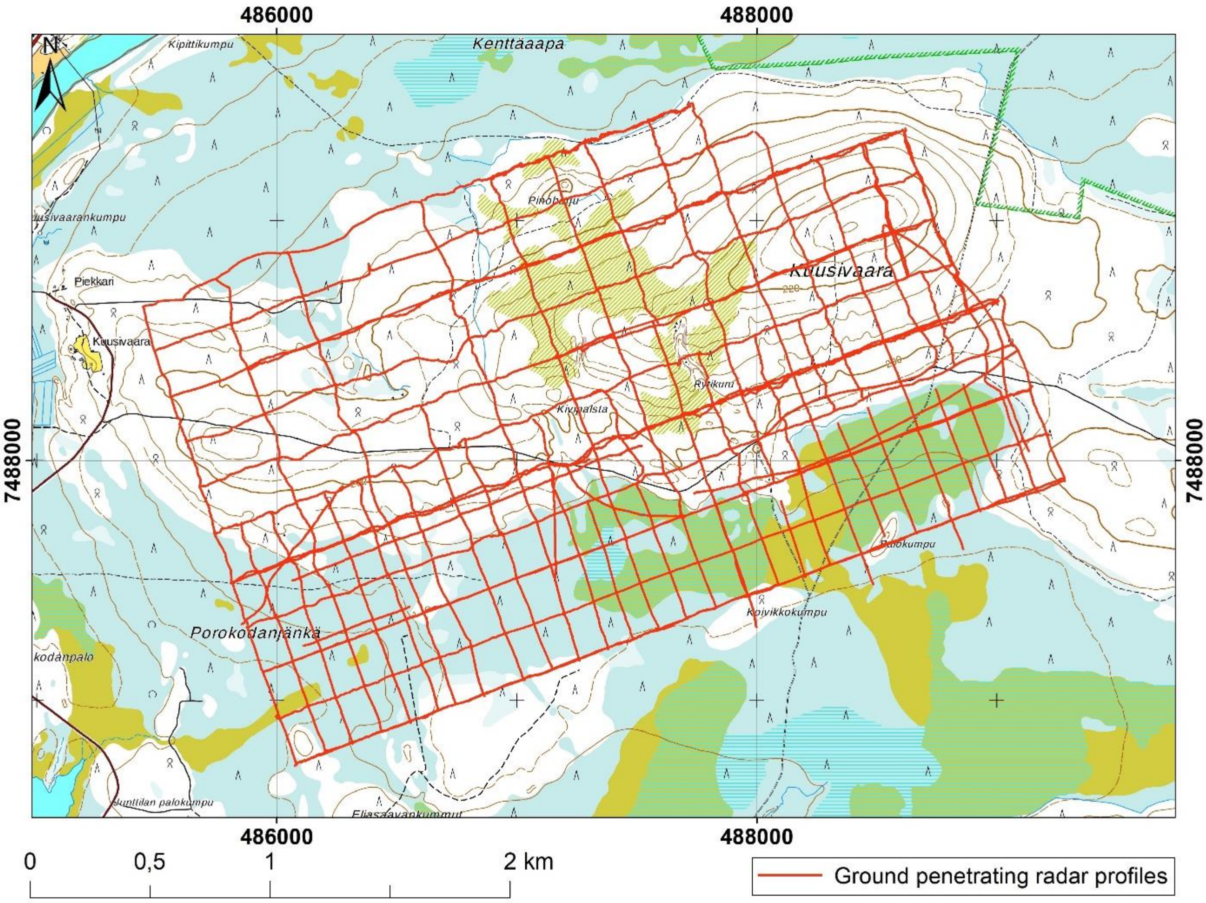

Figure 9: Tracks of the GPR profiles, whose interpreted contacts were used in this study. Background map by National Land Survey of Finland.

The University of Helsinki research team processed and interpreted the GPR data using the ReflexW software by Sandmeier Geophysical Research. Their data of the sediment and bedrock contacts are used in this study.

5.1.4 LiDAR

The National Land of Survey of Finland has produced a digital elevation model of Finland using Light Detection and Ranging (LiDAR) technology (NLS, 2020). The laser measurements used to create the elevation model had a point density of at least 0.5 points/m^2. The model with a cell size of 2 x 2 metres (Korkeusmalli 2m) was utilized in this study to create the topography of the 3D model. The LiDAR surveys over Kuusivaara were performed in 2010. The elevation accuracy of the model is 0.3 m on average and the elevations are given in the N2000 system.

5.2 Methods and materials of this study

5.2.1 Field methods

Sedimentological test pits were excavated in and around Kuusivaara in August 2020. The test pit locations were chosen to cover areas of little or no previous data, to provide information on the features identified from LiDAR data, and to coincide with the junctions in the survey lines of the GPR data to provide reference data points for interpretation of the data.

The test pits were excavated using a tractor excavator (Figure 10). The depth of the excavation was decided individually for each pit evaluating the safety of the pit as well as the stratigraphy. Reaching the bedrock surface was used as a maximum limit, and in some test pits groundwater flow forced further excavation to be ceased. The deepest pit dug was 4 m.

Figure 10: The excavation of the test pit 20TR019.

Before entering any test pit, the top sections of the walls were flattened at an incline to prevent collapses. The test pit walls were then cleaned using a chisel from the top of the wall to the bottom, except for one pit (20TR020) where all observations had to be made from the ground surface due to safety reasons. After cleaning, the walls were studied progressing from the base to the top. Each recognized sediment unit was described regarding its grain-size, colour, compactness, structures, nature of contacts, roundness of clasts and layer dimensions. The test pits were also photographed for later examination and verification of the observations.

Three types of samples were collected from the test pits: geochemical samples (sample size 300 – 500 g), grain-size samples (3 – 5 kg) and heavy mineral samples (approx. 12 litres). Geochemical and grain-size samples were usually collected from the middle to lower parts of each unit directly into the sample bag using a chisel. If there was reason to believe that the geochemistry or grain-size could vary within the unit (e.g. several metres of till), multiple samples were collected from different depths of the same unit. The heavy mineral samples were usually collected from the base of till units and from the weathered bedrock by shoveling material into a bucket, which was then emptied into a large sample bag. Some duplicate geochemical samples were collected for quality control. One sand sample for OSL age determination was also taken and dated in the Laboratory of Geochronology of the University of Helsinki.

After finishing observations and sampling, the test pits were backfilled with the excavated material and the site was flattened and compacted with the tractor excavator. A marker stick was also placed on top of the filled pit.

To provide enough samples for both determining the grain-size distribution and performing the two-step batch leaching tests, all the grain-size samples collected in the field were divided later into two subsamples using the coning and quartering method (e.g. Crosby & Patel, 1995). Each sample bag was emptied onto a plastic sheet, where the material was thoroughly mixed and piled into a cone and the top of the cone was flattened. A rod was placed under the plastic sheet and the cone was divided into two halves by lifting the rod. This procedure was repeated perpendicular to the first division resulting in four quarters, of which the opposite corners were combined into one subsample (Figure 11).

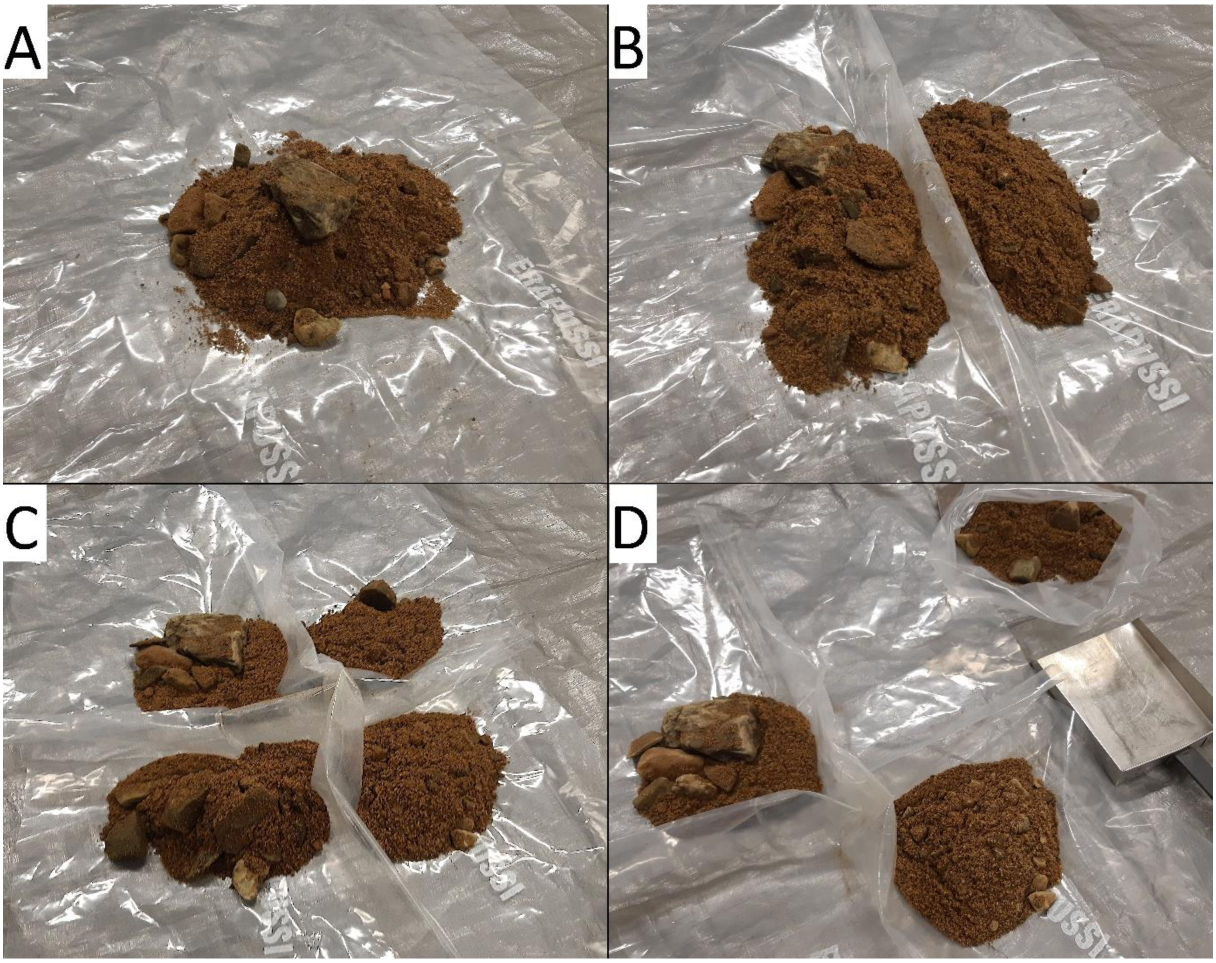

Figure 11: The coning and quartering method used to divide the field samples into two subsamples. The material was mixed and piled into a cone (A), a rod was lifted underneath the plastic sheet to divide the cone into two halves (B & C), and opposing corners of the resulting quarters were combined into a subsample (D).

5.2.2 Re-analysis of the percussion drilled till samples

The Geological Survey of Finland conducted a large-scale geochemical mapping project in Finland between 1971 and 1983 (Gustavsson *et al*., 1979; GTK, 2019b). The resulting data set, named as 'targeting till geochemistry', consists of geochemical characterisation of approx. 385 000 sediment samples. The samples utilised in this thesis were taken in Kuusivaara in 1973 and 1975.

The sampling was done using sampling lines that were oriented as perpendicular as possible to two geometries: the assumed longitudinal axis of the geochemical anomalies and boundaries of the lithological units along the sampling line (Gustavsson *et al*., 1979). The assumed longitudinal axis of the geochemical anomalies was assumed to be the same as the direction of glacial movement during the last glaciation. The sampling interval used was 100 – 400 m and the line interval 500 – 2000 m.

The sample depth varied but was commonly two metres (GTK, 2019b). The goal was to collect the samples from a till bed that was uniform over the area and had a composition that resembled the bedrock (Gustavsson *et al*., 1979). In addition to the single samples, profile sampling was done on every other sampling line on every fourth sampling point. At those points, samples were taken with a one-metre depth interval as deep as the equipment allowed.

The drilling equipment varied during the program, but the samples utilized in this thesis were collected using a Cobra BBM 47 percussion drilling machine (GTK, 2019b). The sample volume varied between 30 and 90 cm^3, which was in most cases enough to provide a sufficient amount of sieved fine fraction for the analysis (Gustavsson *et al*., 1979). After their collection, the samples were dried at 70-80 °C and sieved to < 0.06 mm.

The large number of samples in the programme were analysed using an ARL Model 31000 emission quantometer connected to a Danielsson tape machine (Gustavsson *et al*., 1979). The machine was based on optical emission spectroscopy and analysed 17 elements semi-quantitatively: silicon, aluminium, iron, magnesium, calcium, sodium, potassium, titanium, vanadium, chromium, manganese, cobalt, nickel, copper, zinc, lead, and silver. The concentrations of these elements were calculated by comparing the machine's output voltage to signals analysed from samples of a known composition. The results of these analyses have been reviewed later, for example, by Taivalkoski (2017) in his M.Sc. thesis, where he compared the original results to concentrations analysed with Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-OES) and Graphite Furnace Atomic Absorption Spectroscopy (GFAAS) in aqua regia solution. He found that the concentrations determined using the emission quantometer were several hundred per cent larger compared to the re-analyses. This was because the emission quantometer analysed total concentrations in the samples, but many silicates are not soluble in aqua regia and were thus not represented in the re-analysis.

GTK has stored a large amount of original samples from the study programme up to the present day and allows re-analyses to be performed with the samples. The samples have been stored in their original vials and are kept in the GTK archive facilities in Loppi.

As a part of this thesis study, 113 samples were sent to geochemical re-analysis with modern methods (Figure 12). Of those samples, 93 samples consisted of the fine fraction of the drilled sediments (till, sand or gravel), and 20 samples consisted of drilled weathered bedrock (fine fraction or sieved and crushed).

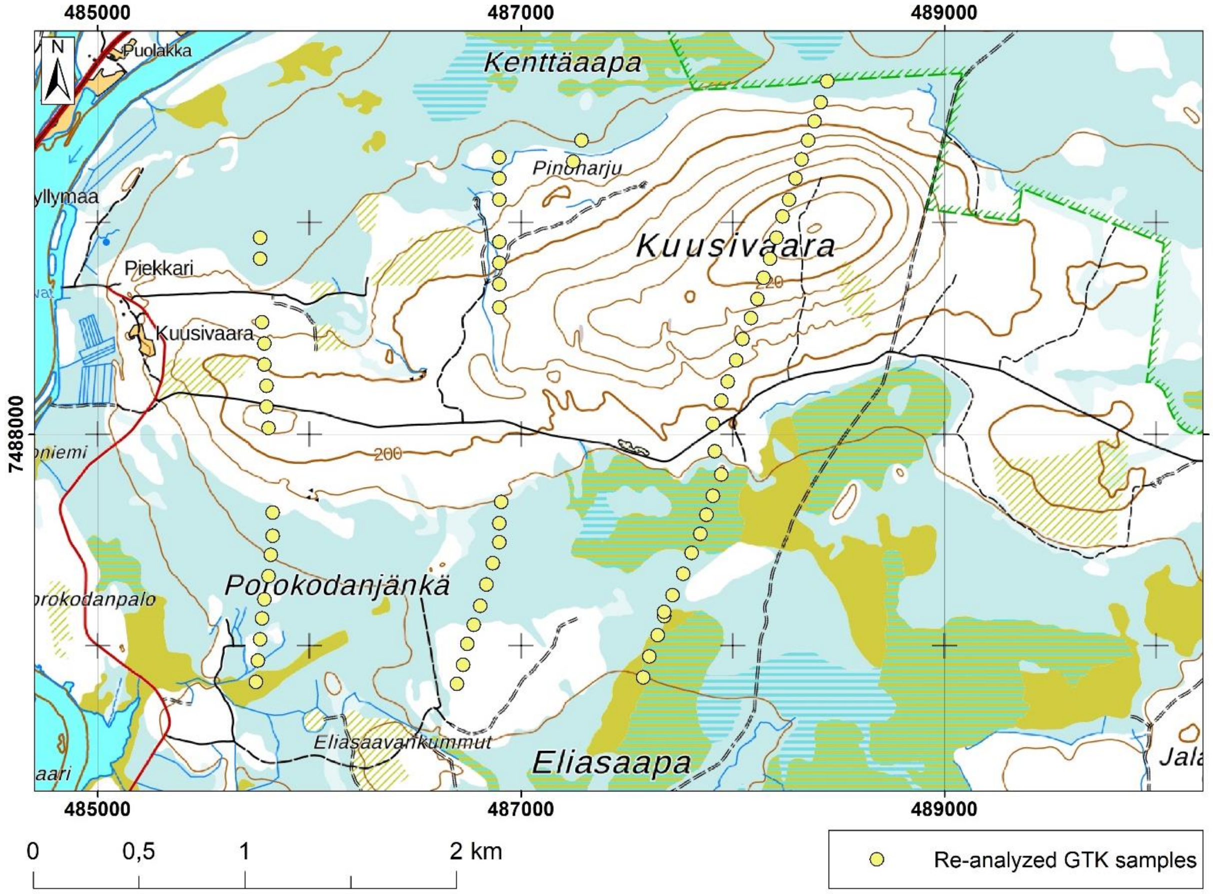

Figure 12: Original sampling locations of the re-analysed GTK samples (GTK, 2019b). Background map by National Land Survey of Finland.

The re-analyses were performed by ALS Minerals in Loughrea, Ireland with the ALS laboratory package 'ME-MS41L: Ultra-Trace Method For Soils Using ICP-MS and ICP-AES'. The method description by ALS (2013) is cited regarding the description below. Subsamples of 0.5 g were taken from the original sample vials and digested with aqua regia in a graphite heating block. The solution was then diluted with deionized water and analysed first by ICP-AES and then ICP-MS. The results were corrected for inter-element spectral interference. The analysed elements included Ag, Al, As, Au, B, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Fe, Ga, Ge, Hf, Hg, In, K, La, Li, Mg, Mn, Mo, Na, Nb, Ni, P, Pb, Pd, Pt, Rb, Re, S, Sb, Sc, Se, Sn, Sr, Ta, Te, Th, Ti, Tl, U, V, W, Y, Zn and Zr.

5.2.3 Geochemical analyses

In addition to the re-analysis of the percussion drilled till samples, geochemical analyses were performed using samples from disturbed samples collected in one-metre intervals by Mitta Oy (see chapter *5.1.2 Drilling data*), and the samples collected from the test pits in this study (see chapter *5.2.1 Field methods*). The analysis method used was the same as the method described in *5.2.2 Re-analysis of percussion drilled till samples*, i.e. the method ME-MS41L in the ALS Minerals laboratory in Loughrea, Ireland, only adding sieving of separate grain-size fractions. The re-analysed, archived samples had been sieved to include only material < 0.06 mm and the samples were analysed as such. The samples from the two recent field work campaigns were analysed using two grain-size fractions from each sample: < 2 mm and < 0.06 mm.

The fraction < 2 mm is required by the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007). The fine fraction (< 0.06 mm) was analysed to enable comparison of the results to the results of the re-analysis of percussion drilled till samples using only one grain-size fraction (< 0.06 mm). Using the results of both grain-size fractions in the recent field work campaigns' samples, a conversion factor was created for the re-analysis results of the percussion drilled till samples for an estimated concentration for the fraction < 2 mm.

This conversion factor was calculated for each element separately, and also separately for the weathered bedrock samples and sediment samples (regardless of sediment type). The relative proportion R of the concentration in the analysis with the fraction < 2 mm to the concentration in the analysis with the fraction < 0.06 mm was first calculated for each sample (Equation 1).

$$relative\ proportion\ R = \frac{concentration < 2\ mm\ (ppm)}{concentration < 0.06\ mm\ (ppm)} \tag{1}$$

The median value of these relative proportions of the samples was selected for each element as the conversion factor. The conversion of the re-analysis results of the drilled till samples to the fraction < 2 mm was performed with Equation 2.

$$converted\ concentration < 2\ mm\ (ppm) = concentration < 0.06\ mm\ (ppm) \cdot C_f \tag{2}$$

, where C_f is the conversion factor of each element calculated as the median value of the relative proportions.

The solubility of metals was tested using 18 sediment samples. Many factors affect the solubility of metals in sediments: for example, the pH of the solvent water and the system, the water flow velocity and continuity, and temperature (Kuusela-Lahtinen *et al*., 2012). Thorough testing of the solubility behaviour of a sediment sample requires long tests (weeks to months) with varying conditions using, for example, the column test. However, a relatively quick estimate of the solubility in some range of conditions can be achieved using the two-step batch leaching test.

The two-step batch leaching test was chosen for this study to gather initial estimates for the solubility of metals in the different Kuusivaara sediment units, and to compare the results to the relevant guidelines set in the legislation. The samples tested were chosen with two considerations: to include all the sediment units observed in the test pits of this study and to include samples from different parts of the study area. The tests were performed by ALS Minerals in Czech Republic with the ALS laboratory package S-W-LEACH-INERT-2-33 following the standard EN 12457-3.

5.2.4 Slug tests

Slug tests are hydrogeological tests carried out in groundwater wells to estimate the water permeability of the medium surrounding the well (Bouwer & Rice, 1976; Bouwer, 1989). Water permeability is defined as the property of a material describing the ease with which water flows through the material (Fitts, 2013). The water permeability of sediments depends on, for example, their grain-size distribution, packing, and effective porosity (Rosas *et al*., 2014). Water permeability can be expressed in varying units (e.g. cm/s, m/s, m/d), but in this thesis only m/s is used.

Mathematically, water permeability is expressed in Darcy's law as follows (Fitts, 2013) (Equation 3):

$$Q = -K\frac{dh}{ds}A \tag{3}$$

, where Q is water flow [m^3/s], K is water permeability [m/s], $\frac{dh}{ds}$ is the hydraulic gradient, and A is the area of the cross-section through which the water flows [m^2].

In slug tests, water is quickly removed (rising-head test) or added (falling-head test) to the well, and the recovery of the water level to its initial position is measured. Based on the measurements and the geometry of the well and the surrounding aquifer, the water permeability of the aquifer can be calculated.

Slug tests were carried out in groundwater wells in Kuusivaara in July 2020. Rising-head tests were done by pumping water from the well using an inertia pump or a Solinst 410 peristaltic pump and measuring the recovery of the groundwater level back to its original, static state. Falling-head tests were done by adding water to the well using a bucket or a beaker, and a funnel (Figure 13). The volumes of extracted or added water were between 0.3 – 40 litres.

Figure 13: The setup for initiating a falling-head slug test at the well 18HYD026.

The recovery of the water level was measured using a Solinst Levelogger Edge M10 pressure datalogger. The absolute pressure measurements were corrected into water level readings using the Solinst Levelogger 4.4.0 software and data from a Solinst Barologger, which was situated above the water level in the well 18HYD033. Measurement intervals of 0.5 and 1 seconds were used. The accuracy of the water level readings is ± 0.5 cm according to the manufacturer Solinst (2020).

The results were analysed using the method described by Bouwer & Rice (1976) and updated later by Bouwer (1989). The analysis method can be applied for both confined and unconfined aquifers and it is based on the Thiem equation for groundwater flow into a well. The values for the geometry of the well and the aquifer used in the analysis were taken from the well descriptions provided by AA Sakatti Mining Oy. The analysis of the results was completed using a spreadsheet created by the United States Geological Survey (Halford & Kuniansky, 2016), which performs the calculations involved in the analysis automatically when the geometrical values and water level measurements are provided. The calculated recovery graph was fitted to the data points in the spreadsheet manually.

Bouwer (1989) described a so-called double line effect, which can be present in the test results and should be considered in the data analysis. The water level recovery graph might show a steeper (quicker) rate of recovery when the test is initiated (i.e. first straight line in the graph), but relatively quickly in the recovery, the recovery rate slows down resulting in a less steep recovery rate for the later parts of the test (i.e. second straight line in the graph). This is usually due to gravel pack or a developed zone of sediments around the well, which has a higher water permeability than the aquifer around the well. Thus, in the beginning of the recovery the gravel pack or developed zone affects the recovery rate until it is saturated (falling-head) or drained (rising-head) after which the recovery is dependent on the groundwater flowing from the undisturbed aquifer.

Because slug tests are performed to measure properties of the aquifer, in case of a double line effect the results should be analysed using the second straight line of the water level recovery graph, as was done in this study. A line fitted for the data points of the second straight line will correspond to the water permeability of the surrounding aquifer.

5.2.5 Determining water permeability using the grain-size distribution

Since slug tests could only be performed at eight separate locations in the study area and only in some of the observed sediment units, water permeability values were calculated based on grain-size distributions of sediment samples to supplement the data on the water permeability of the sediments. Slug tests provide *in situ* results of the water permeability and are as such regarded as the most reliable method for water permeability testing in this thesis. For all sediment units that were slug tested in this study, the slug test results were considered more reliable than the calculated water permeability values.

Grain-size distribution has been used as a parameter to determine the water permeability of sediments for over a hundred years (e.g. Slichter, 1902). Theoretical equations producing reliable water permeability values have not been developed, but tens of empirical equations linking grain-size distribution to water permeability can be found in literature (Rosas *et al.*, 2014). Some of these were developed to be used with a specific type of sediments (e.g. fluvial sediments) and some with sediments of all grain-sizes. The equations do not use the complete grain-size distribution, but rather one or multiple fractions of the complete distribution. Most commonly used are the d_{10}, d_{17} and d_{50} with the subscript numbers meaning 10 %, 17 % or 50 % of the sample mass, respectively, consisting of smaller particles than the diameter (d) in millimetres (Powrie, 2004).

All these empirical equations, even restricted to specific types of sediments, yield only estimates of the true water permeability with errors up to several hundred per cent (Rosas *et* al., 2014). Thus, the results must be regarded as supporting in comparison to more reliable methods.

When studying the hydraulic conductivity of heterogenous sediments, including glacial and glaciofluvial sediments, MacDonald *et al.* (2012) found that the finest 10 % fraction of the sediments (d_{10}) affected the hydraulic conductivity of the sediments the most. Salarashayeri & Siosemarde (2012) found the same to be valid when researching sands. Leroueil *et al.* (2002) studied compacted tills and their hydraulic conductivity and concluded that the fine fraction content of tills affects their hydraulic conductivity.

As the sediments in Kuusivaara consist mostly of tills and sands, the above-described tendencies, regarding the finest fractions of tills and sands correlating best with hydraulic conductivity, are relevant in choosing the equation for estimating the water permeability. The two equations used in this study are the Sauerbrei equation and Kozeny-Carman equation. Rosas *et al.* (2014) described the Sauerbrei equation as suitable for sediments with d_{17} below 0.5 mm. The Kozeny-Carman equation is described by Rosas *et al.* (2014) to be suitable for silts, sands and gravelly sands. Both equations have been used in Finnish environmental and geological studies previously (e.g. Tarvainen *et al.*, 2011; Kaipainen & Valjus, 2018; Salonen *et al.*, 2018).

The Sauerbrei equation (Vukovic & Soro, 1992 as cited in Rosas *et al.*, 2014) is presented in Equation 4:

$$K\left[\frac{m}{s}\right] = \beta\frac{g}{\nu}\frac{n^3}{(1-n)^2}d_{17}^2 \tag{4}$$

, where β is $3.75 \cdot 10^{-3}$ [unitless], g is the gravitational acceleration [m/s^2], ν is the kinematic viscosity of water [mm^2/s], n is the bulk porosity [unitless], and d_{17} is the diameter in the grain-size distribution that 17 % of the sample mass is smaller than [mm].

Kozeny-Carman equation (Kozeny, 1953; Carman 1956; both as cited in Rosas *et al*., 2014) is presented in Equation 5:

$$K\left[\frac{m}{s}\right] = \beta\frac{\rho g}{\mu}\frac{n^3}{(1-n)^2}d_{10}^2 \tag{5}$$

, where β is 1/180 [unitless], ρ is the density of water [kg/dm^3], g is the gravitational acceleration [m/s^2], μ is the dynamic viscosity of water [mPa · s], and n is the bulk porosity [unitless], and d_{10} is the diameter in the grain-size distribution that 10 % of the sample mass is smaller than [mm].

Both equations include the porosity of the sample as a parameter. Lind & Lundin (1990) report that in a data set of 210 Swedish till samples the total porosity varied between approx. 20-45 %. The porosity of fluvial sand and gravel deposits varies between approx. 10-35 % (Frings *et al*., 2011). In this study, a porosity value of 0.4 was used in estimating the water permeability based on the porosity values reported by Lind & Lundin (1990) and Frings *et al*. (2011), and the porosity values used in previous estimations in Kuusivaara by Salonen *et al*. (2018). Also, the kinematic viscosity of water is present in the equations. The kinematic viscosity value of water at 5 °C, 1.519 · 10^{-6} m^2/s, and density of water value 0.9982 kg/dm^3 were used in the calculations of this study (Crittenden *et al*., 2012).

The grain-size distributions of 29 sediment samples were measured for this study by Mitta Oy in their laboratory in Oulu, Finland, using wet and dry sieving. These sediment samples were collected from the test pits excavated in this study. The d_{10} and d_{17} values were determined manually from the grain-size distribution curves provided by the laboratory.

5.2.6 3D modelling

In this thesis, all 3D modelling was done using the Leapfrog Geo 5.1 software by Seequent. The 3D modelling process consisted of both implicit and explicit modelling.

Leapfrog Geo performs implicit modelling automatically when a model is created in the software and data to be used in the model is defined. The algorithm used by the software is FastRBF, which is an algorithm based on radial basis functions (Seequent, 2020). In this thesis, implicit modelling was performed using lithological data from the test pits, soil drilling sites and peat drilling sites as well as contact surface points from GPR data (either lower or upper contact of a certain unit).

The contacts identified from the extensive GPR data set over Kuusivaara provided a comprehensive data set for the 3D modelling. However, the facies data in the interpretations by the University of Helsinki was often definite only on whether the recognized units were bedrock, sedimentary or organic (peat), but not on the exact facies of the sediments (e.g. till, weathered bedrock).

To provide more detailed correlations for the contacts, *in situ* data such as test pits and soil drilling data were used as the primary reference to link the contacts to different sediment units when creating the model. The interpreted contacts were examined in Leapfrog Geo in 3D view in comparison with the *in situ* data, facies interpretations by the University of Helsinki, and the topography. Based on this analysis, the contact was classified as either the upper or lower contact of a certain sediment unit.

If no reference sites were located along a GPR profile or in the near vicinity, the contacts were cross-referenced to the contacts of another crossing GPR profile, whose contacts had been interpreted using *in situ* reference sites. Some GPR contacts could not be referenced to any other data, and those were interpreted considering the geology and geomorphology of the surroundings, the depth and geometry of the contacts, and the facies interpretations by the University of Helsinki. Some contacts were also discarded from the 3D modelling because the contact could not be linked reliably to any sediment unit. All the GPR contacts classified to one sediment unit (e.g. lower contact of peat) were combined into one point cloud file.

The 3D modelling process requires that units from different test sites, which are interpreted to be of the same origin and composition (e.g. a sandy till as the topmost unit), are named consistently so that Leapfrog Geo considers them to be of the same unit. Thus, a framework stratigraphy was developed for the study area in Kuusivaara. The *in situ* data sets, mainly test pits and soil drilling data, were examined over the whole study area to develop the framework stratigraphy. Subsequently, all data used in the 3D modelling was renamed to only include lithologies of this framework stratigraphy. GPR contacts were also referenced using this stratigraphy to be compatible with the other data.

The model created with implicit modelling was controlled manually by evaluating the continuation and thickness of the units in comparison with the *in situ* data and topography. This was done by inspecting cross sections across the model. When explicit modifications to the implicitly created model were deemed necessary, the software was given polylines to further define the geometry of a surface and the model was then recalculated taking into account the additional data. Explicit modelling was especially used to define the outer perimeters of the sediment units, but also, for example, to adjust the thicknesses of the sediment units in areas with little or no other data.

Leapfrog Geo calculates volumes for each of the units in the model automatically. In addition, the volumes of the modelled sediment units were calculated using a cut-off depth of 3 m below the ground surface to provide a more realistic estimate of the volume of sediments viable for excavation (e.g. situated above groundwater level).

The volumes of the 3D model were converted to tonnages using the bulk density of different sediment classes. As no measurements of bulk density were performed as part of this study, the bulk density values were estimated using data from literature.

In literature, till bulk densities have been reported with a relatively consistent range. Eyles & Sladen (1981) describe lodgement tills in Northumberland, England, having bulk densities of 1900 – 2300 kg/m^3. Clarke *et al*. (2008) describe also tills in England, and report values in the range 1870 – 2280 kg/m^3. The former Finnish Road Institute (Tielaitos, 1993) has reported typical bulk densities for tills in Finland, giving separate values for different grain-size compositions. The bulk densities were 1940 – 2240 kg/m^3 for silty till, 1830 – 2240 kg/m^3 for sandy till, and 2040 – 2240 kg/m^3 for gravelly till.

For sorted sediments, Culshaw *et al*. (1991) report bulk densities of 1400 – 2150 kg/m^3 for sand, and 1450 – 2300 kg/m^3 for gravel. The Finnish Building Information Foundation (Rakennustietosäätiö, 2015) has reported for Finnish sorted sediments bulk densities of 1820 – 1950 kg/m^3 for sand, and 2200 – 2240 kg/m^3 for gravel.

The bulk densities of tills from the several sources above are consistent with one another. The tills in Kuusivaara are most similar in setting to the Finnish tills described by Tielaitos (1993), and thus the bulk density values given in that description are used in this study. For sorted sediments, the lower end of the density range differs between the sources. The values given by Rakennustietosäätiö (2015) are based on Finnish sediments and are meant to be used in sediment excavation for construction, which is also the case in Kuusivaara. Thus, those values are used in this study. The bulk densities used in the volume-to-mass conversions are summarised in Table 4. These values represent total bulk density, including natural moisture content, for sediments situated above the groundwater table.

Table 4: Bulk density values for sediments situated above the groundwater table used in the volume-to-mass conversion of the 3D model (Tielaitos, 1993; Rakennustietosäätiö, 2015).

Sediment class	Bulk density [kg/m^3]
Silty till	1940 – 2240
Sandy till	1830 – 2240
Gravelly till	2040 – 2240
Sand	1820 – 1950
Gravel	2200 - 2240

6 Results

6.1 Test pit results

In total, 11 test pits were excavated between the 24th and 27th of August 2020 (Figure 14). Two of the pits were located south of Kuusivaara in Eliasaavankummut, eight in the Kuusivaara hill and one was located southeast of Kuusivaara on an unnamed extension of the Kuusivaara hill (called Kuusivaara kaakko on the log). Six of the pits reached the bedrock surface at 1 – 2.1 m. The five pits, which were completed without reaching the bedrock, ranged between 2.5 and 4.0 m of excavated sediment depth. Groundwater was observed in six of the pits.

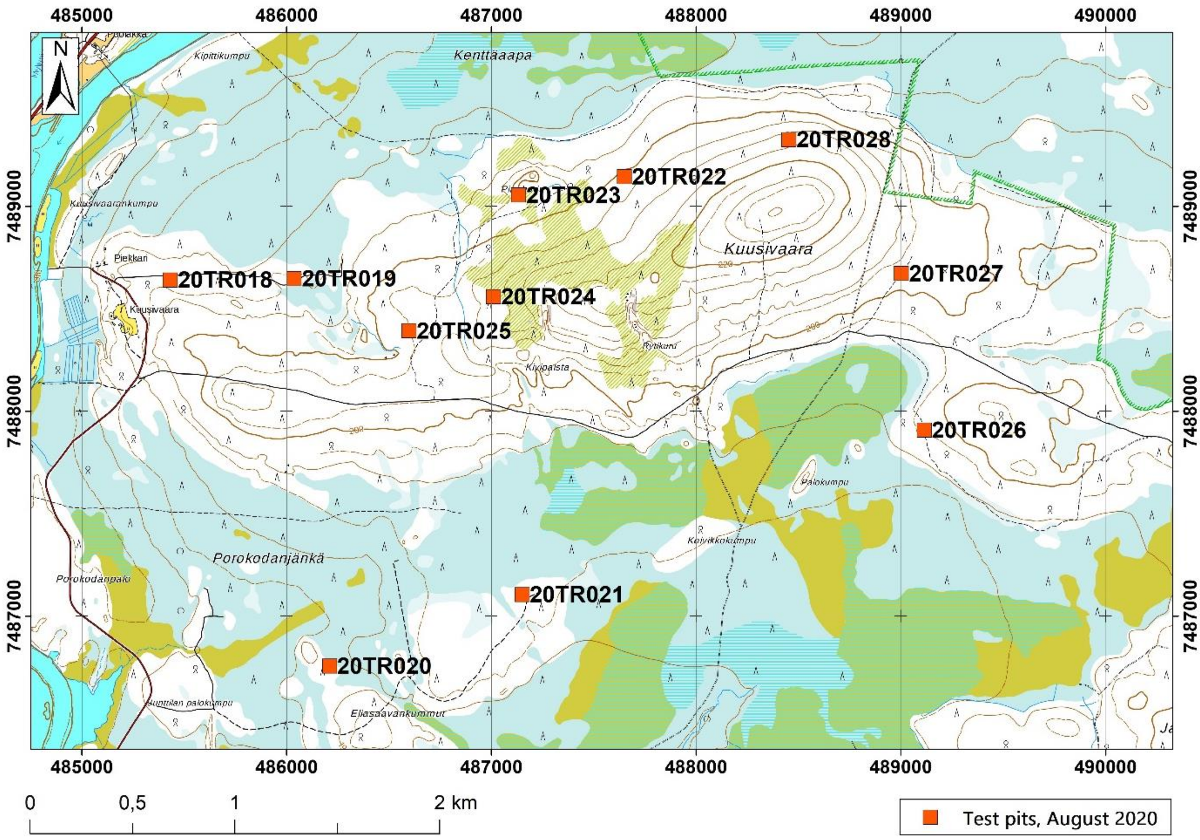

Figure 14: Locations of the excavated test pits. Background map by National Land Survey of Finland.

The test pit 20TR018 was situated in the northwestern part of the Kuusivaara hill (Figure 15). The excavation stopped at 1.9 m below the ground surface (b.g.s.) and weathered bedrock was encountered at 1.2 m b.g.s. There was no groundwater seepage into the pit. The uppermost unit of the pit was composed of brown, washed till with a gravel matrix. The lowermost 70 cm of the till unit contained larger clasts than the upper parts. The bottom-most 5 – 10 cm of the till unit was composed of a layer of sand and fine gravel. The lower contact of the till at 1.2 m b.g.s. was sharp.

The weathered bedrock beneath the till unit was massive and contained iron-stained (rusty) stripes in places. An ice wedge cast of fine to medium sand cut the weathered bedrock with a width of 24 cm in the upper contact of the weathered bedrock. The ice wedge cast occurred through the test pit in an approx. vertical plane orientated southeast – northwest (170 – 350°).

Eight samples were collected from the pit. Three of the samples were taken for geochemical analysis, two for grain-size determinations, two for heavy mineral analysis and one for OSL age determination. The age determination result of the OSL sample collected from the ice wedge cast is 77 000 ± 15 000 years BP (palaeodose 168 ± 25 Gy and dose rate 28.4 ± 0.799 mGy/s).

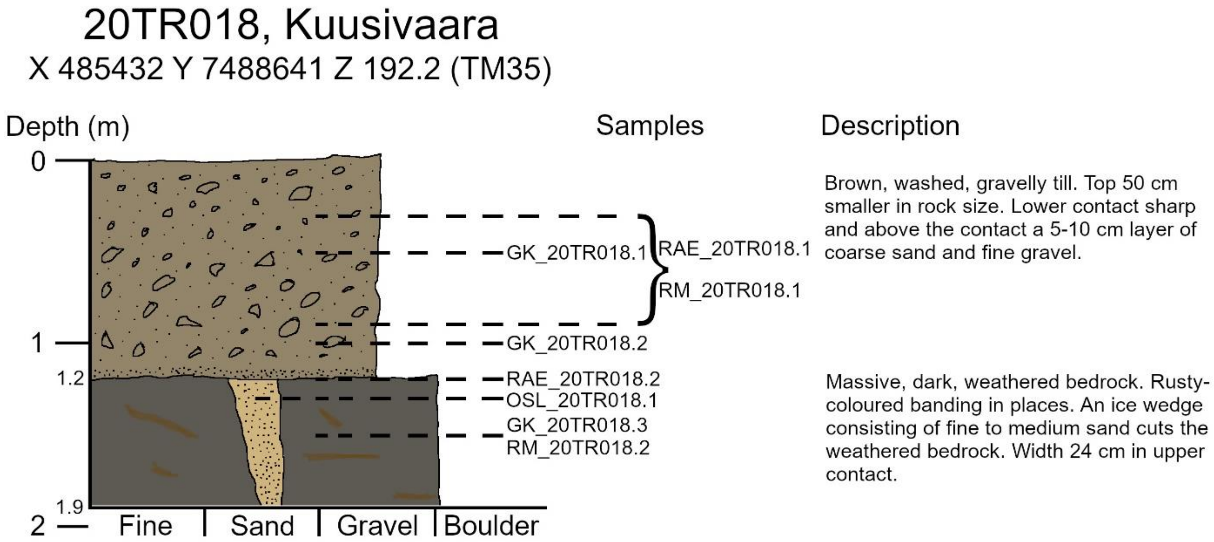

Figure 15: A sedimentary log of the test pit 20TR018.

The test pit 20TR019 was situated in the northwestern part of Kuusivaara (Figure 16). The excavation stopped at 2.8 m b.g.s. and the bedrock was not reached. The groundwater level in the pit was at 1.6 m b.g.s. and groundwater flow into the pit prevented detailed observations below 1.9 m b.g.s. The only observed unit of the pit was composed of brown, washed till with a sand matrix. The uppermost 70 cm of the unit was matrix-dominated and larger clasts were scarce. The till contained more large clasts and had deformation and load structures in the matrix between 0.7 m and 1.2 m b.g.s. Below 1.2 m b.g.s., the till matrix contained more gravel and large clasts were scarce in the till. A layer of large clasts (diameter > 20 cm) was reached at 2.8 m b.g.s.

Seven samples were collected from the pit. Three of the samples were taken for geochemical analysis, three for grain-size determinations and one for heavy mineral analysis.

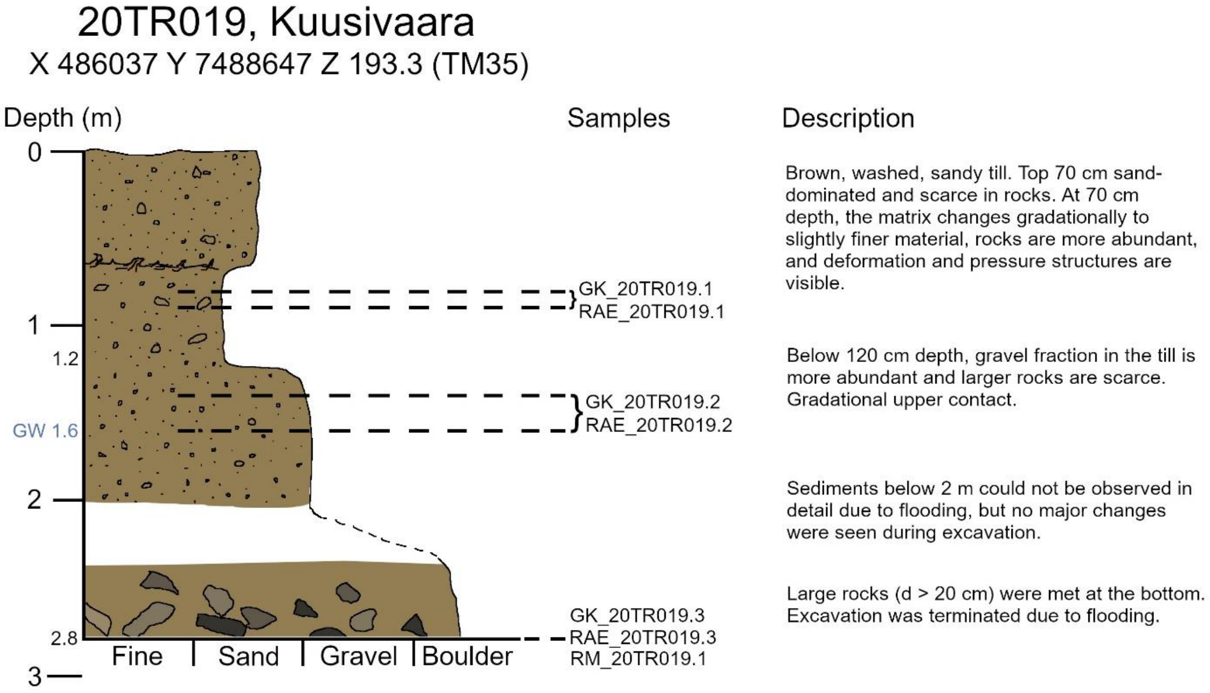

Figure 16: A sedimentary log of the test pit 20TR019.

Test pit 20TR020 was situated approx. 1 km south of Kuusivaara on Eliasaavankummut (Figure 17). The excavation stopped at 4.0 m b.g.s. and the bedrock was not reached. The groundwater level in the pit was at 3.8 m b.g.s. The uppermost unit of the pit was composed of brown, massive till with a sand matrix. Large clasts were scarce in the uppermost till unit. The lower contact of the uppermost till at 2.0 m b.g.s. was gradational. A boulder pavement with large clasts, both rounded and angular, occurred beneath the uppermost till. The lower contact of the boulder pavement at 2.7 m b.g.s was gradational. The lowermost sediment unit in the pit was a blueish grey till with a silt matrix. The lowermost silty till was matrix-dominated between 2.7 m and 3.7 m b.g.s., but contained abundant large clasts (diameter > 20 cm) below 3.7 m b.g.s.

Eight samples were collected from the pit. Three of the samples were taken for geochemical analysis, three for grain-size determinations and two for heavy mineral analysis.

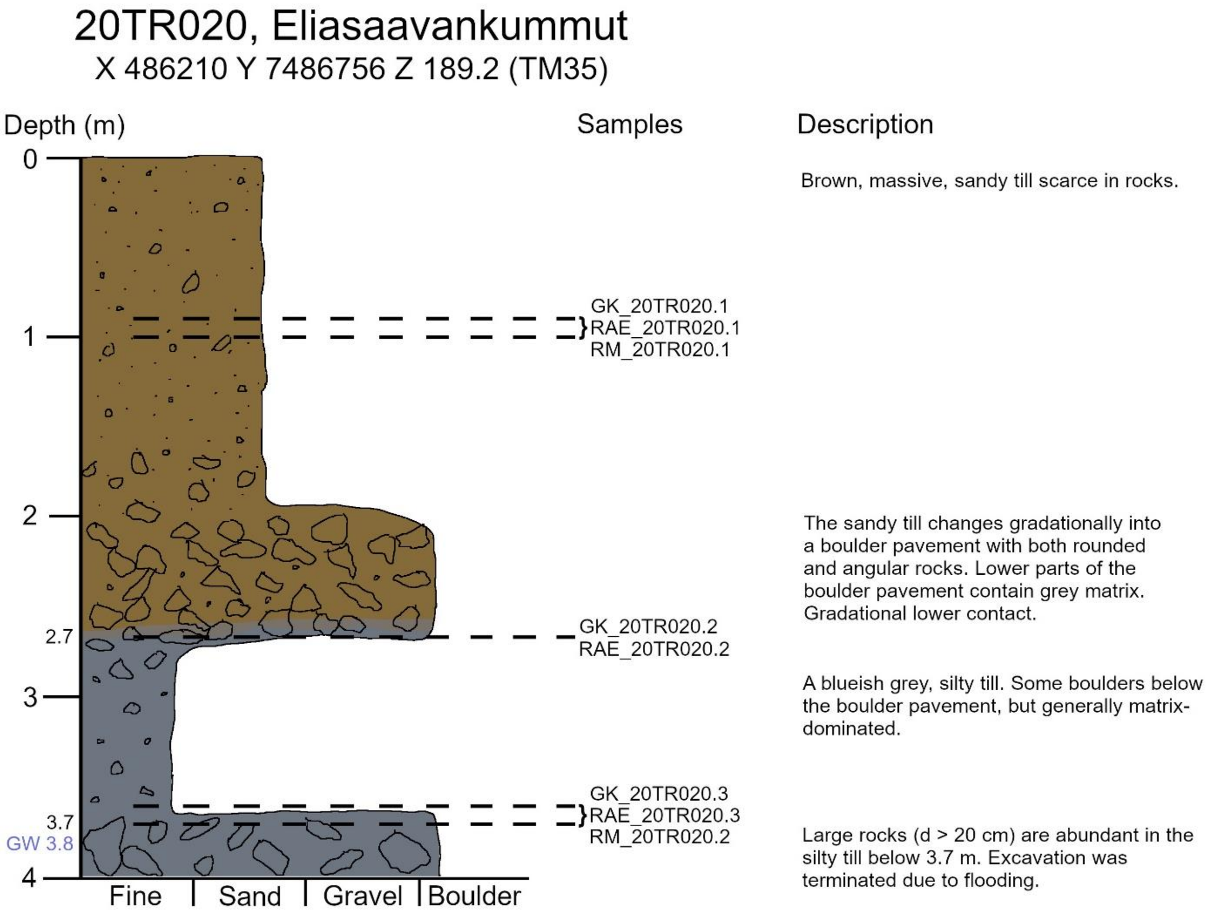

Figure 17: A sedimentary log of the test pit 20TR020.

Test pit 20TR021 was situated approx. 1 km south of Kuusivaara on Eliasaavankummut (Figure 18). The excavation stopped at 2.0 m b.g.s. and the mafic volcanite bedrock was reached at 1.9 m b.g.s. The groundwater level in the pit was at 1.8 m b.g.s. The uppermost unit of the pit was composed of brown till with a sand matrix. Clasts with a diameter of > 10 cm were scarce in the till in the uppermost 1.3 m, but the till was abundant in large clasts (diameter = 20 – 30 cm) and had lenses of sand below 1.3 m b.g.s.

Five samples were collected from the pit. Three of the samples were taken for geochemical analysis, one for grain-size determination and one for heavy mineral analysis.

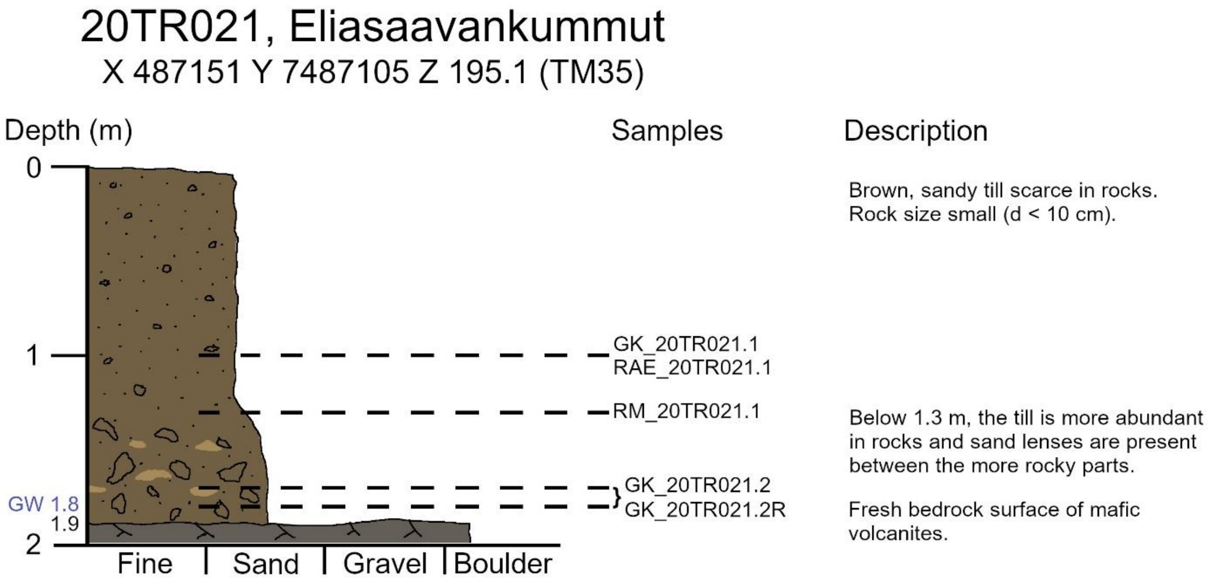

Figure 18: A sedimentary log of the test pit 20TR021.

Test pit 20TR022 was situated on the northern slope of Kuusivaara (Figure 19). The excavation stopped at 2.9 m b.g.s. and the bedrock was not reached. The groundwater level in the pit was at 2.9 m b.g.s. The uppermost unit of the pit was composed of brown till with a sand matrix. The diameter of clasts in the uppermost till was generally 10 – 30 cm. A till clast fabric measurement at 1.0 m b.g.s. showed that elongated clasts were oriented from 250 – 320° to 70 – 140° with a significant amount of vertically orientated clasts. The uppermost till started to grade into sand at 1.2 m b.g.s. and had a sharp lower contact at 1.4 m b.g.s.

A horizontally bedded sand unit occurred beneath the uppermost till. The upper contact of the sand unit was deformed and its elevation varied. The lower contact of the sand unit at 1.5 m b.g.s. was sharp. A gravel unit with reverse grading occurred beneath the sand unit. In the upper parts of the gravel unit, the clast diameter was generally 10 – 20 cm. The gravel unit graded into coarse sand and fine gravel towards the base of the unit and contained clasts of rounded and granitic material. The lower contact of the gravel unit at 2.4 m b.g.s. is sharp. Instead of the gravel, a sand layer occurred between 1.5 – 2.4 m b.g.s. on one wall of the test pit. One sample (RAE_20TR022.5) was taken from this sand layer instead of the gravel unit. A greyish brown till unit with a fine sand matrix occurred beneath the gravel unit.

Eleven samples were collected from the pit. Four of the samples were taken for geochemical analysis, five for grain-size determinations and two for heavy mineral analysis.

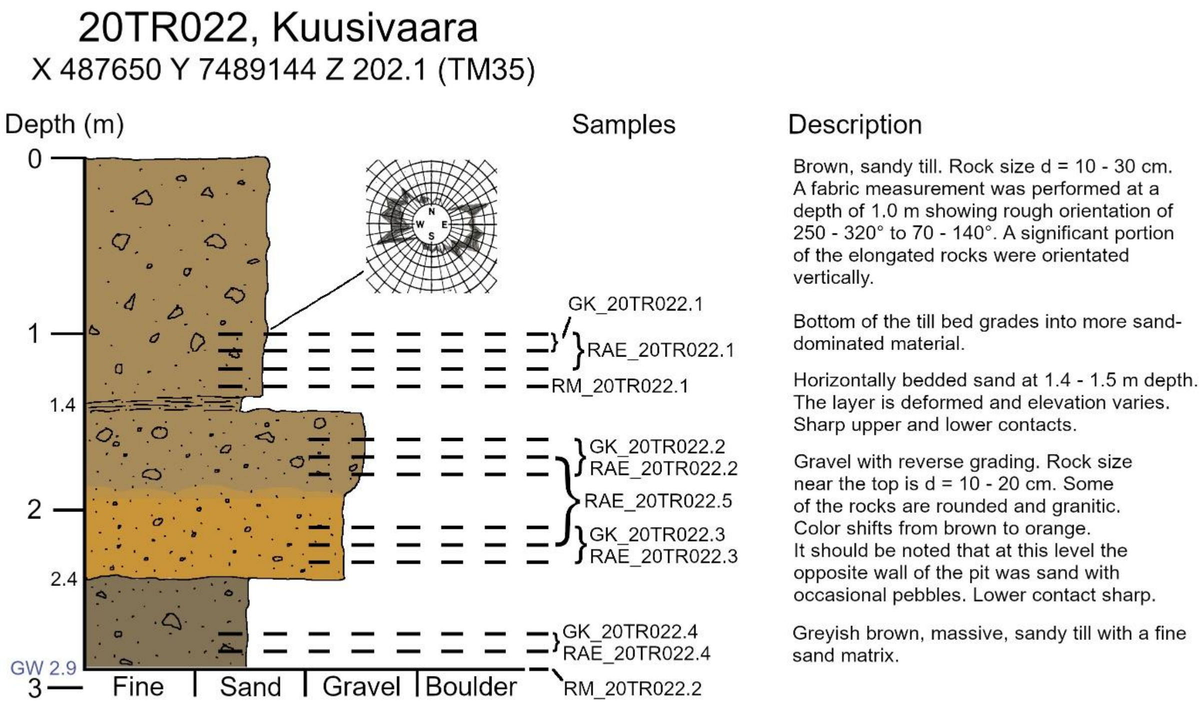

Figure 19: A sedimentary log of the test pit 20TR022.

Test pit 20TR023 was situated on the southern slope of Pinoharju, in the northern part of Kuusivaara (Figure 20). The excavation stopped at 3.3. m b.g.s. and the bedrock was not reached. The groundwater level in the pit was at 2.6 m b.g.s. The uppermost unit of the pit was composed of orange-hued sand with flow structures. The lower contact of the sand unit at 0.7 m b.g.s. was gradational. A brown till unit with sand matrix occurred beneath the sand unit. The till unit had some large clasts (diameter 10 – 20 cm) in the uppermost 50 cm of the unit, but below that clasts were small and scarce. The till unit had lenses of fine sand at 2.5 m b.g.s. and below 3 m b.g.s. the till was abundant in large clasts and had a greyish colour.

Twelve samples were collected from the pit. Five of the samples were taken for geochemical analysis, five for grain-size determinations and two for heavy mineral analysis.

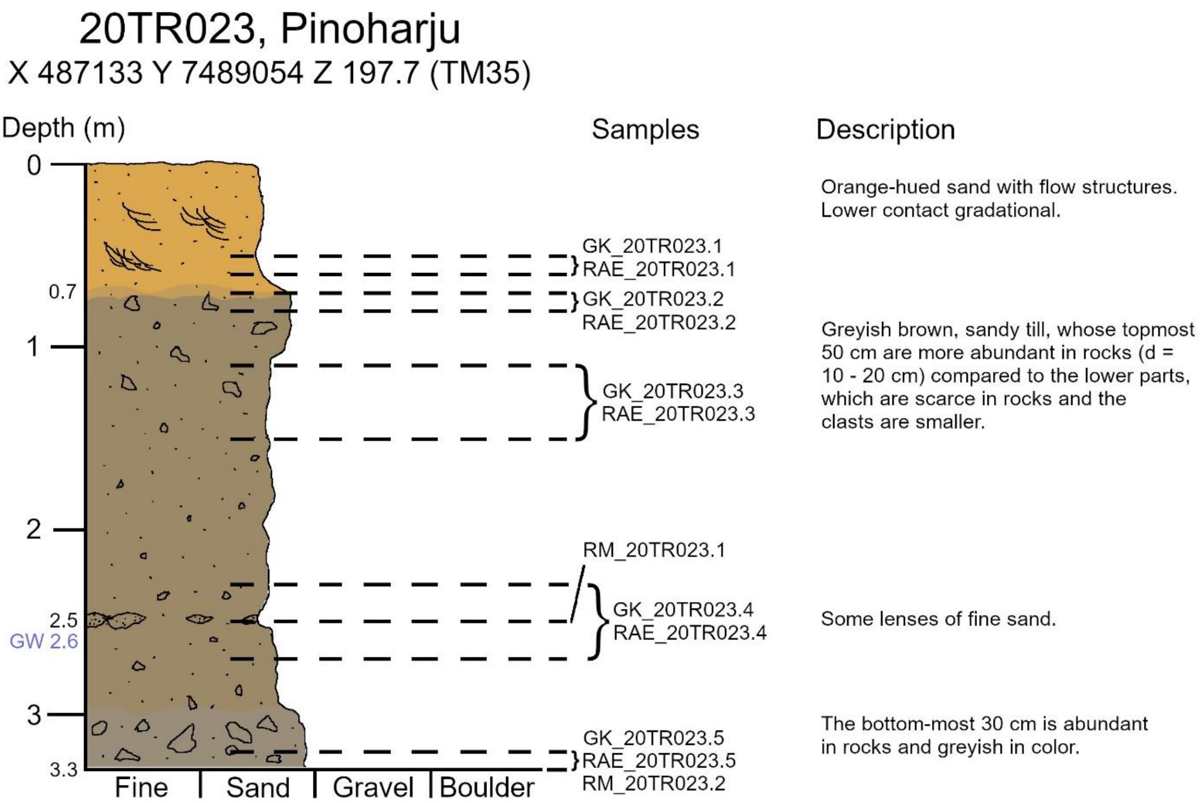

Figure 20: A sedimentary log of the test pit 20TR023.

Test pit 20TR024 was situated on the central part of the Kuusivaara hill (Figure 21). The excavation stopped at 1.2 m b.g.s. and the blocky and weathered mafic volcanite bedrock was reached at 1.0 m b.g.s. There was no groundwater seepage into the pit. The uppermost unit of the pit was composed of greyish brown till with a sand matrix, abundant in large, angular clasts (diameter 10 – 30 cm). The lower contact of the till unit at 1.0 m b.g.s. was sharp.

Three samples were collected from the pit. One of the samples was taken for geochemical analysis, one for grain-size determination and one for heavy mineral analysis.

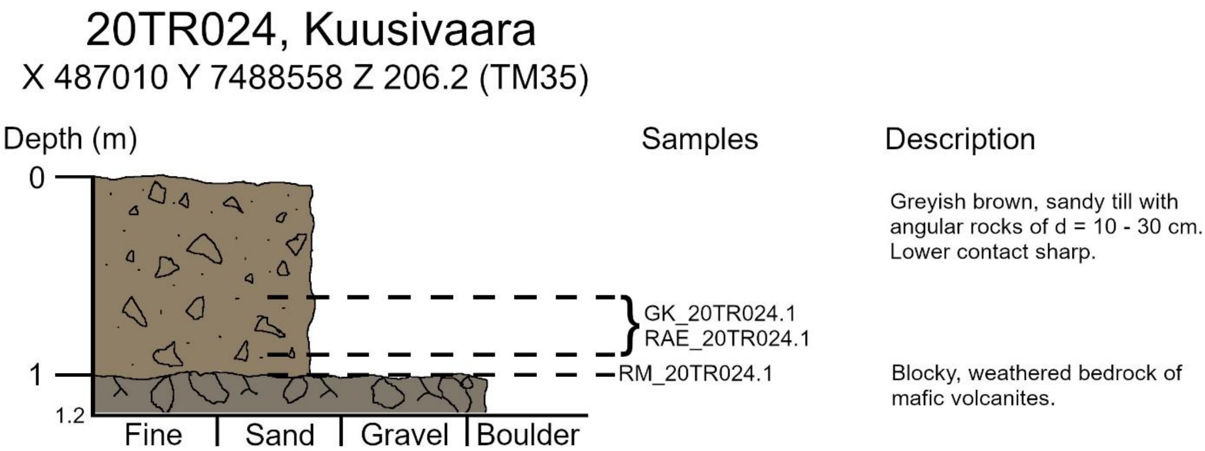

Figure 21: A sedimentary log of the test pit 20TR024.

Test pit 20TR025 was situated on the central part of the Kuusivaara hill (Figure 22). The excavation stopped at 2.1 m b.g.s. and the weathered mafic volcanite bedrock was reached at 1.8 m b.g.s. The groundwater level in the pit was at 2.1 m b.g.s. The uppermost unit of the pit was composed of brown till with sand matrix, abundant in large clasts. The clasts in the till were both angular and rounded and contained also granitic material. The uppermost 70 cm of the till unit contained less clasts than the lower parts. The lower contact of the till at 1.8 m b.g.s. was gradational with blocks of weathered bedrock.

Seven samples were collected from the test pit. Three of the samples were taken for geochemical analysis, two for grain-size determinations and two for heavy mineral analysis.

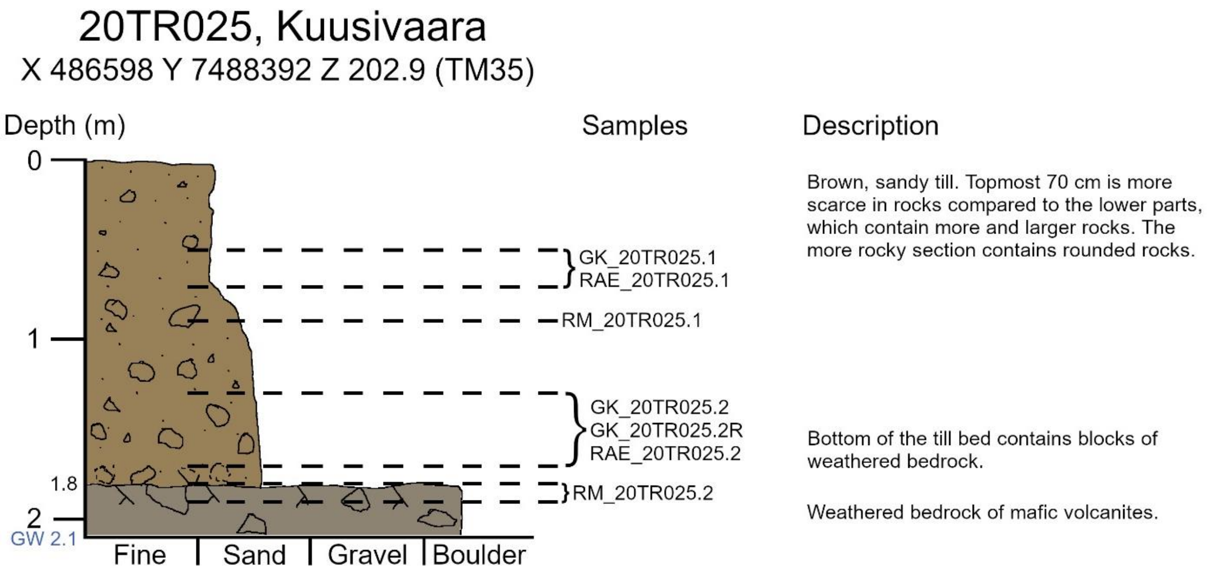

Figure 22: A sedimentary log of the test pit 20TR025.

Test pit 20TR026 was situated approx. 700 m southeast of the Kuusivaara hill (Figure 23). The excavation stopped at 2.1 m b.g.s. and the blocky, weathered mafic volcanite bedrock was reached at 1.4 m b.g.s. There was no groundwater seepage into the pit. The uppermost unit of the pit was composed of greyish brown till with sand matrix, abundant in angular clasts. A till clast fabric measurement at 0.7 m b.g.s. showed two orientation maxima for elongated clasts: from 220 – 230° to 40 – 50°, and from 340° to 160°. However, nearly half of the elongated clasts were vertical. The till unit was abundant in material from the weathered bedrock in the bottom-most 30 cm and had a sharp lower contact at 1.4 m b.g.s.

Seven samples were collected from the test pit. Three samples were taken for geochemical analysis, two for grain-size determinations and two for heavy mineral analysis.

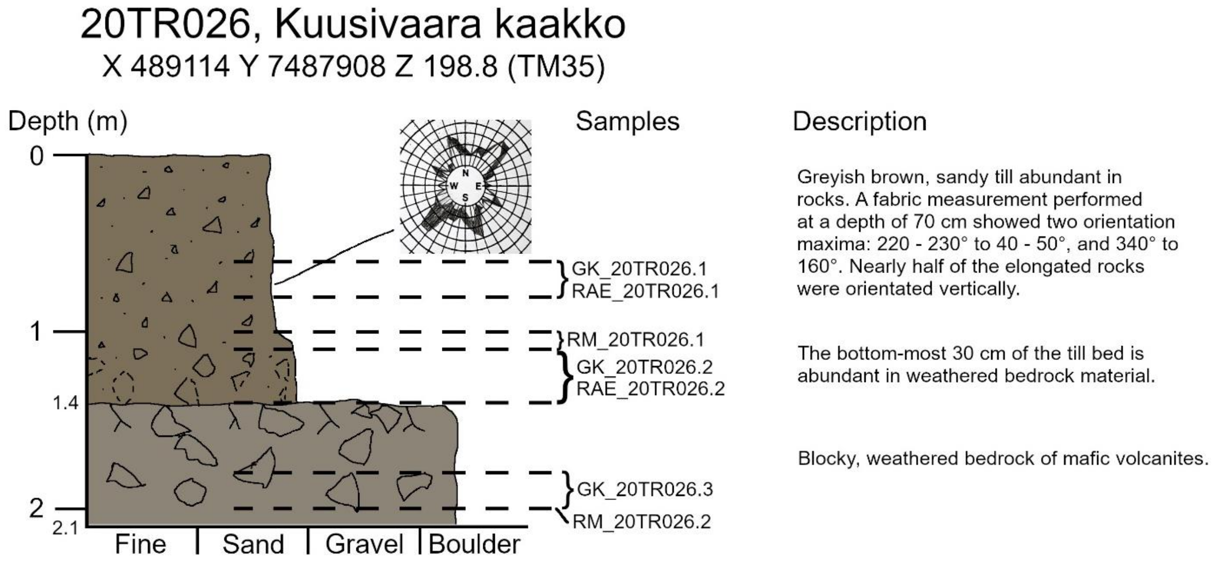

Figure 23: A sedimentary log of the test pit 20TR026.

Test pit 20TR027 was situated on the southeastern slope of Kuusivaara (Figure 24). The excavation stopped at 2.5 m b.g.s. and the bedrock was not reached. There was no groundwater seepage into the pit. The uppermost unit of the pit was composed of loose, brown till with a sand matrix. Large clasts were scarce in the uppermost till. The lower contact of the uppermost till at 0.9 m b.g.s. was gradational. A unit of brownish orange medium sand occurred beneath the uppermost till. The sand unit had loading structures and lenses and the elevations of its upper and lower contact varied. The lower contact of the sand unit at approx. 1.4 m b.g.s. was gradational. A compact brown till unit with a sand matrix, abundant in large clasts, occurred beneath the sand unit. The lowermost till unit had a boulder pavement below its upper contact and the clasts in the till were rounded and granitic.

Eight samples were collected from the test pit. Three of the samples were taken for geochemical analysis, three for grain-size determinations and two for heavy mineral analysis.

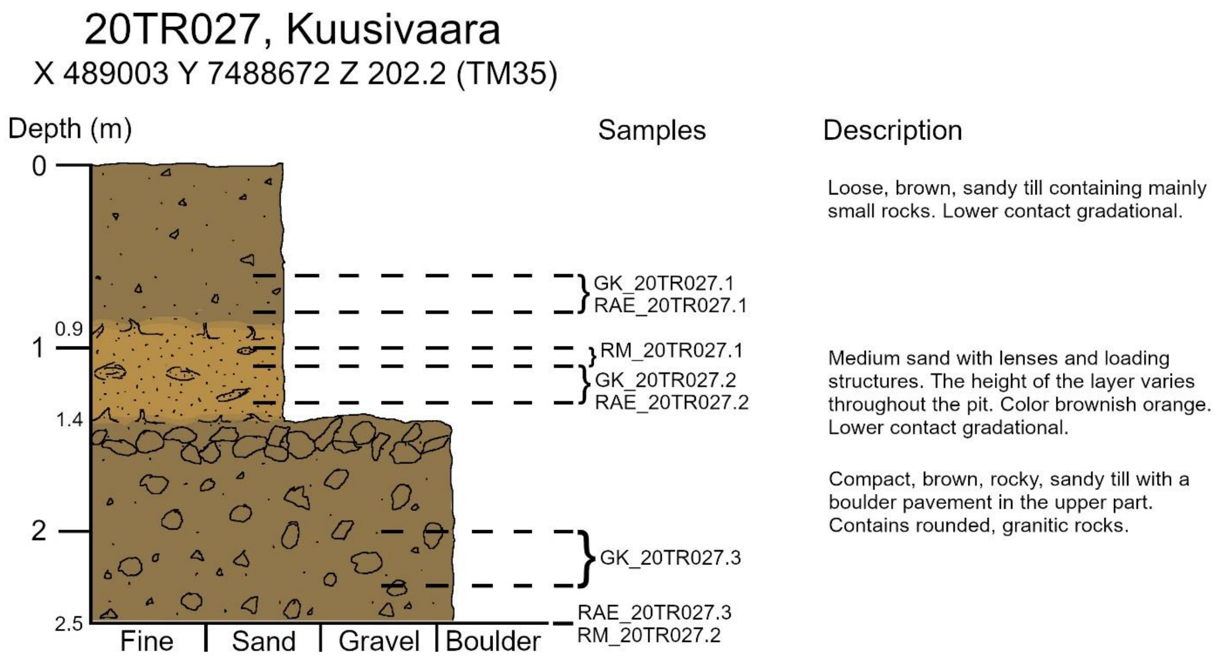

Figure 24: Sedimentary log of the test pit 20TR027.

Test pit 20TR028 was situated on the northern slope of Kuusivaara (Figure 25). The excavation stopped at 2.3 m b.g.s. and the mafic volcanite bedrock was reached at 2.1 m b.g.s. There was no groundwater seepage into the pit. The uppermost unit of the pit was composed of brown, loose till with a sand matrix, abundant in angular clasts. The lower contact of the uppermost till at 0.9 m b.g.s. was sharp. A compact brown till unit, 0.4 m thick, occurred beneath the uppermost till. This compact sandy till unit had a finer matrix than the uppermost till and contained abundant large clasts and fissility structures in the fine matrix. The lower contact of the compact till at 1.3 m b.g.s was sharp. The lowermost sediment unit in the pit was a sandy till, similar to the uppermost till unit with angular clasts.

Six samples were collected from the test pit. Three of the samples were taken for geochemical analysis, two for grain-size determinations and one for heavy mineral analysis.

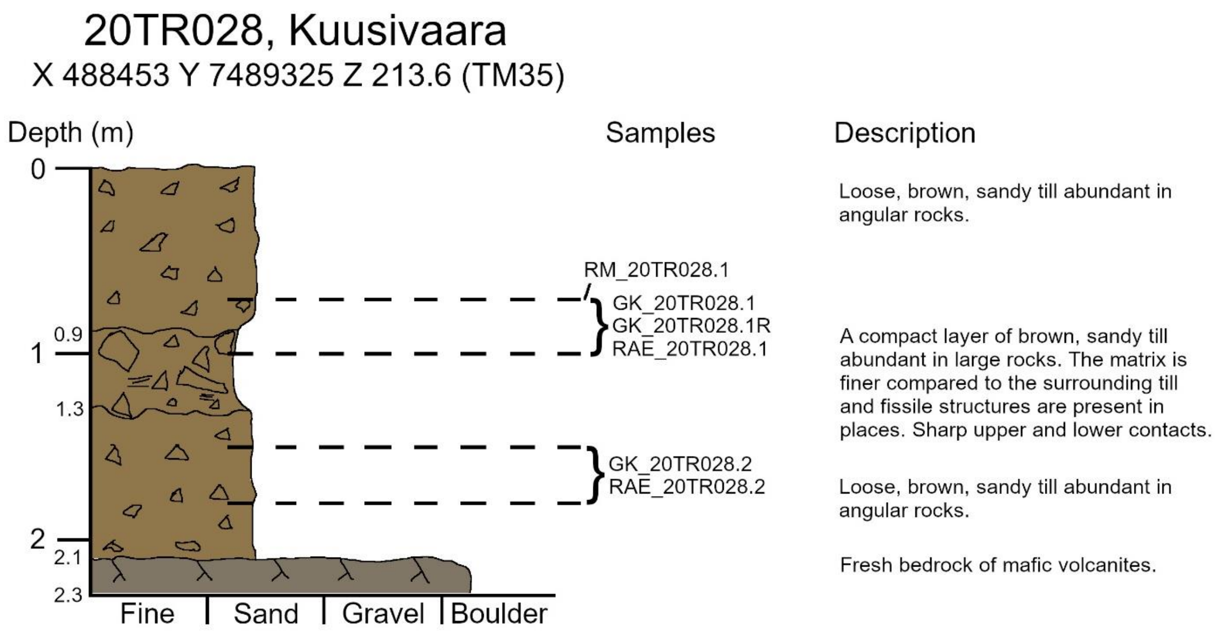

Figure 25: A sedimentary log of the test pit 20TR028.

6.2 3D modelling results

As described in *5.2.6 3D modelling*, a framework stratigraphy was developed encompassing all the observed sediment units in the Kuusivaara area. The stratigraphy and description of the nine units is presented in Table 5. The complete stratigraphy of all nine units has not been observed anywhere in the study area so the stratigraphy is a composite.

Table 5: The framework stratigraphy used to classify all the sedimentary data in the 3D modelling.

Sediment unit	Description
Peat	Peat cover on the wetlands
Surface sand	Sands on the ground surface or directly below peat
Upper sandy till	The topmost sandy till, often on the ground surface
Gravel	Gravel below the upper sandy till
Inter-till sand	Sand below the upper sandy till
Lower sandy till	Sandy till separated from the upper sandy till by a sorted sediment unit (i.e. gravel, inter-till sand)
Silty till	Silty till below the upper sandy till
Weathered bedrock	Weathered upper part of the bedrock
Bedrock	Fresh (un-weathered) bedrock

One sediment unit observed in the field was not included in the framework stratigraphy. This was a surface gravel unit with thicknesses of 0.5 – 0.9 m observed in three AFRY Finland Oy test pits on the southern slope of Kuusivaara. These gravel observations were modelled as upper sandy till due to limited lateral continuity and scarce data of the gravel unit as well as its low observed thicknesses.

The lower sandy till comprises *in situ* observations of sandy tills that are separated from upper sandy till by a sorted sediment unit. This observed separating unit is gravel in the northern slopes of Kuusivaara and inter-till sand in the southeastern slopes of Kuusivaara. Based on *in situ* observations, it is not clear that the sandy till below gravel in the northern slopes and sandy till below inter-till sand in the southeastern slopes are co-genetic. For modelling purposes, they were nevertheless modelled as part of the same unit based on their similar facies (sandy till) and position in the stratigraphy.

The 3D model (Figure 27) was created with an outer boundary of a N-S oriented rectangle with corners situated at (485007, 7486527) and (490041, 7489725) (ETRS-TM35FIN) resulting in a 5 x 3.2 km model area (Figure 26). This outer boundary was defined to encompass all of the study area, but areas of the model outside the study area shown in Figure 26 should be viewed as uncertain and tentative. This is due to lack of any other data than pre-existing topographic and geological maps.

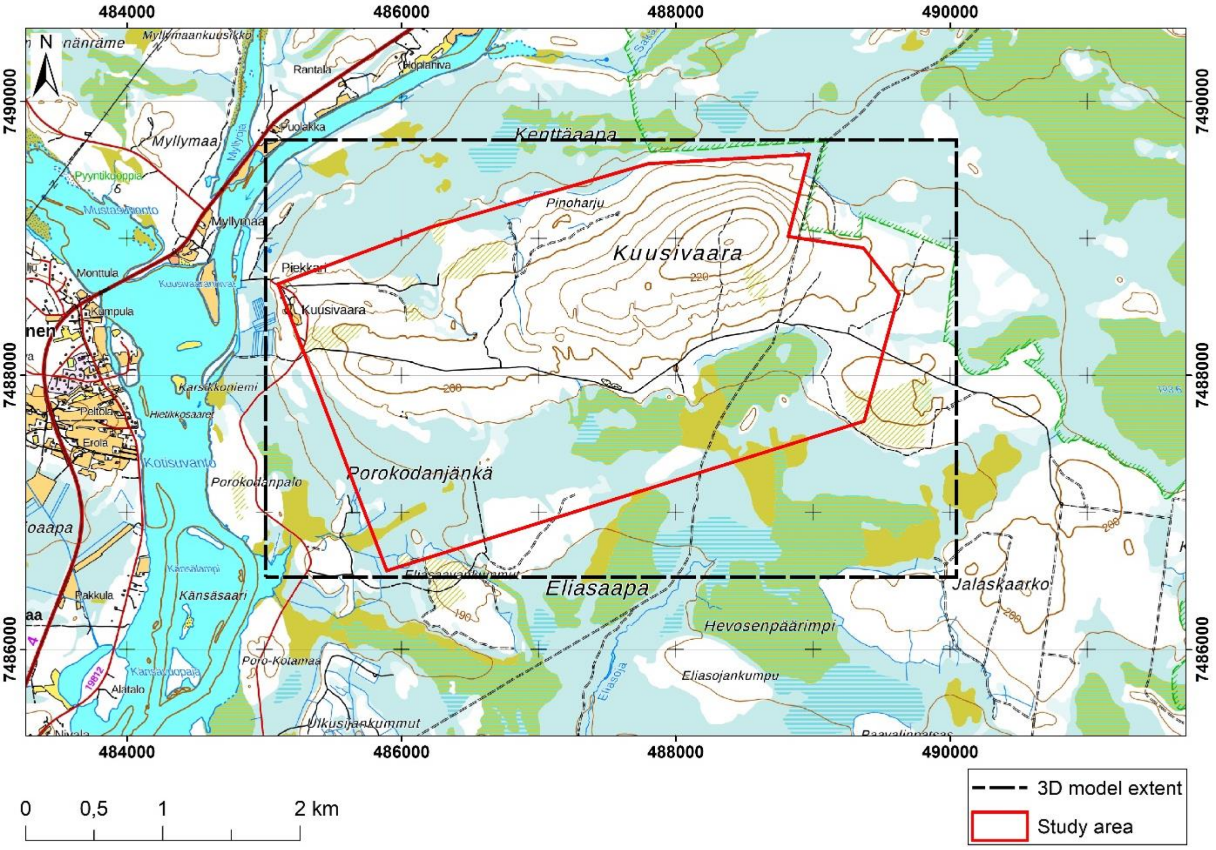

Figure 26: Extent of the created 3D model and the study area over which there was sufficient data for reliable modelling of the subsurface.

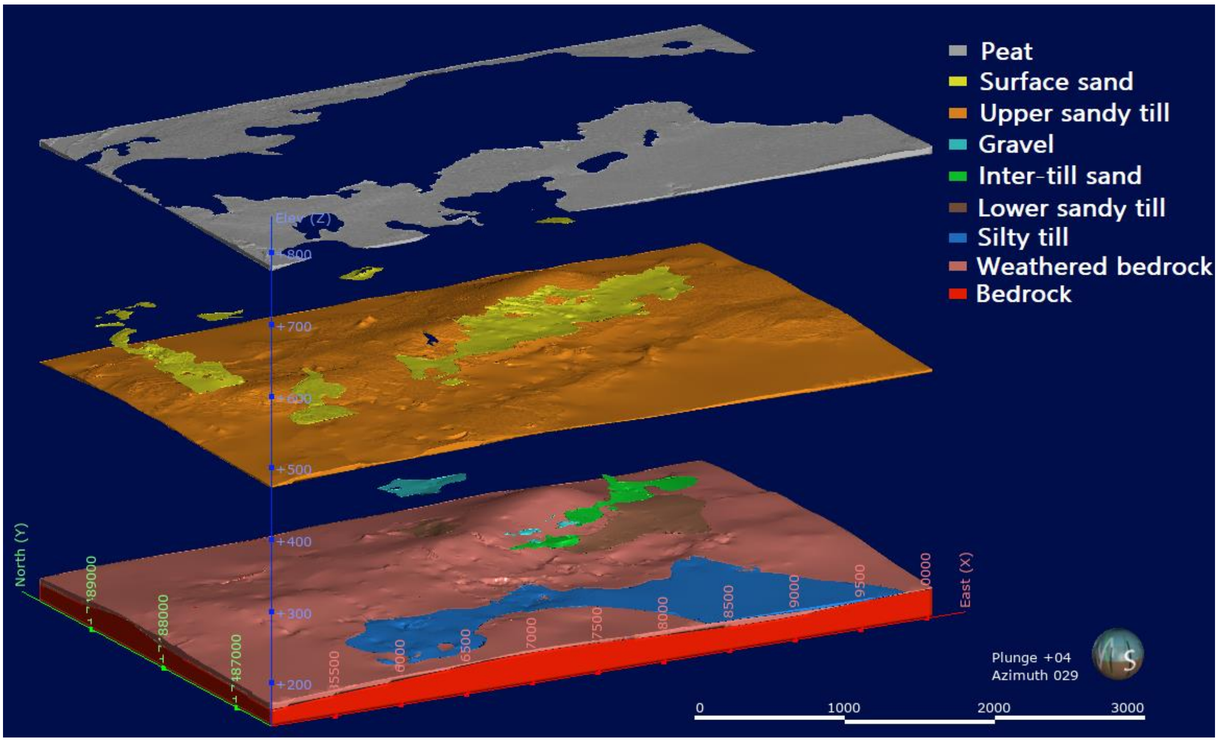

Figure 27: An exploded view of the finished 3D model. Elevation scale should be ignored.

The bedrock was modelled to span over the complete model area and to be eroded by the overlying units based on their lower contacts. The *in situ* and GPR data available for modelling in this study did not enable reliable modelling of the bedrock and weathered bedrock as separate units. Even though the model was created with bedrock and weathered bedrock as separate layers, based almost fully on GPR interpretations, the results should be viewed considering the two in combination representing bedrock regardless of its weathered or un-altered nature.

The weathered bedrock in the model covers the whole modelling area (Figure 28). It outcrops only in small areas within the gorges near the ridge of Kuusivaara. The modelled unit is almost entirely based on the GPR interpretations, which are supported by the bedrock observations in the test pits and soil drilling sites.

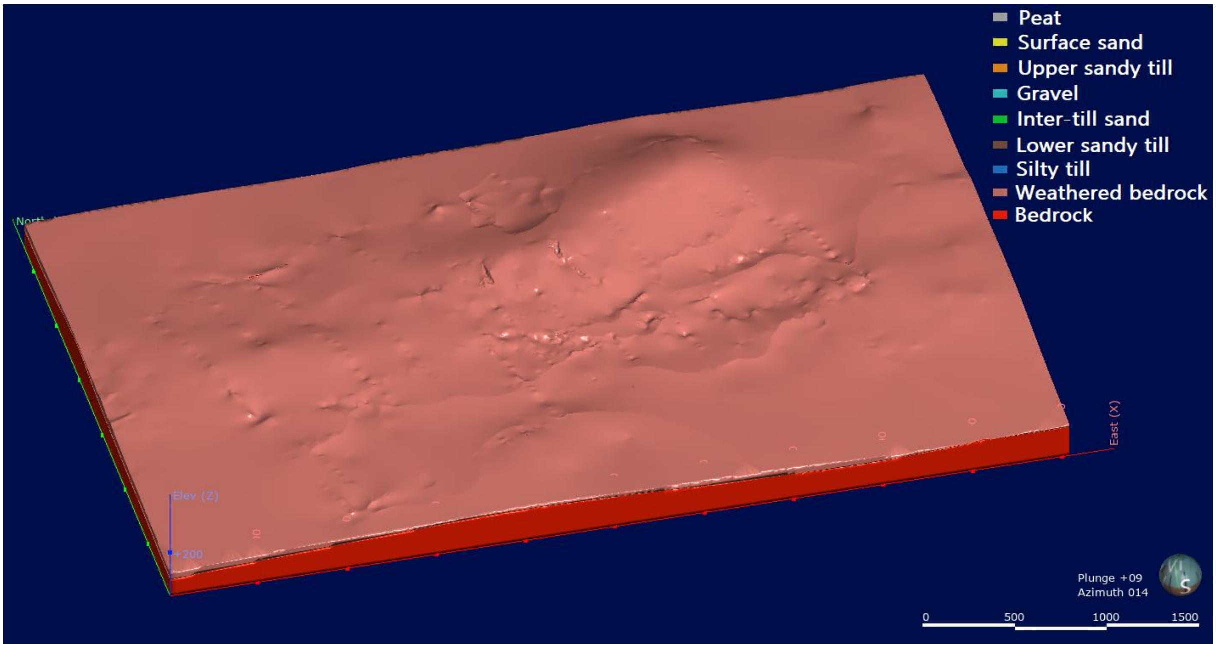

Figure 28: A view of the 3D model with all units overlying the weathered bedrock in the stratigraphy removed from view.

The silty till in the model is present in limited parts of the mire areas south of Kuusivaara (Figure 29). The unit does not outcrop anywhere in the model. The thickness of the unit varies mostly between 2 – 3 m. The modelled unit is mostly based on observations of the silty till in three soil drilling sites on the mire areas south of Kuusivaara and in one test pit on mineral soil southwest of the Kuusivaara hill. The unit was found in the GPR interpretations only in a few picked contacts. The continuation of the till towards the southeast, outside the essential study area, is tentative in the model due to a lack of data.

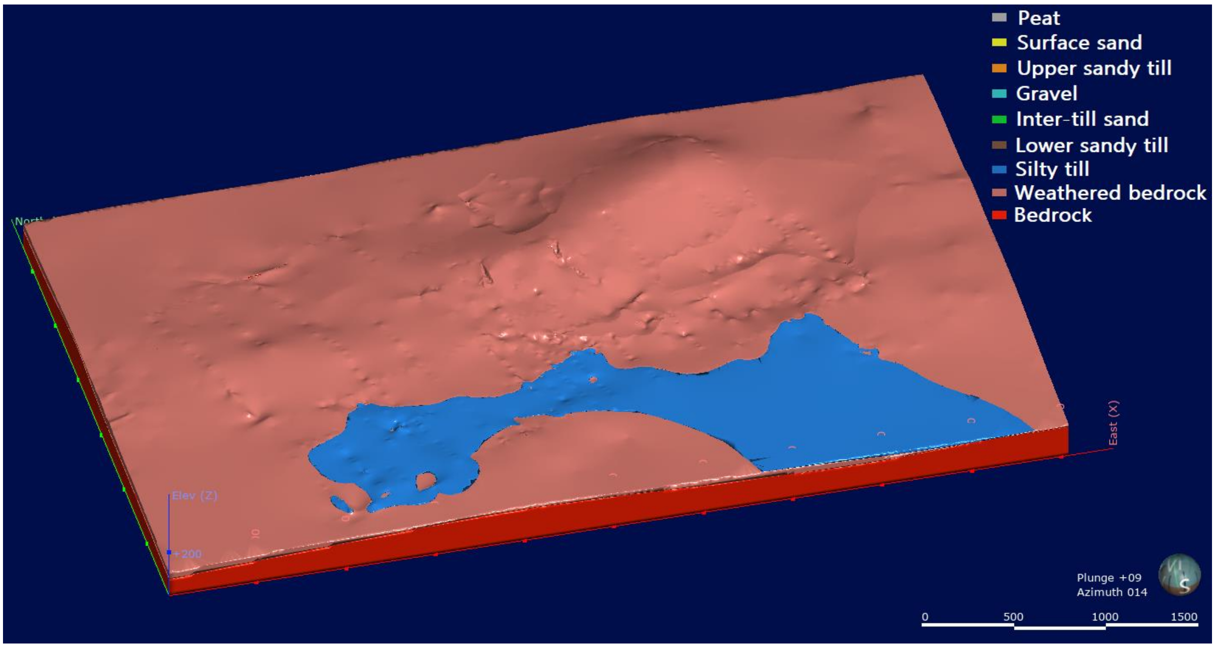

Figure 29: A view of the 3D model with all units overlying the silty till in the stratigraphy removed from view.

The lower sandy till in the model is present in limited areas on the southeastern and northern slopes of Kuusivaara (Figure 30). The unit does not outcrop anywhere in the model. The thickness of the unit varies mostly between 1 – 3.5 m in the northern slope, and 2 – 4 m in the southeastern slope of Kuusivaara. The modelled unit is mostly based on the observations obtained from three test pits in the southeastern slope and one test pit in the northern slope of Kuusivaara. Only a few picked contacts of the unit could be found in the GPR interpretations, all on the southeastern slope.

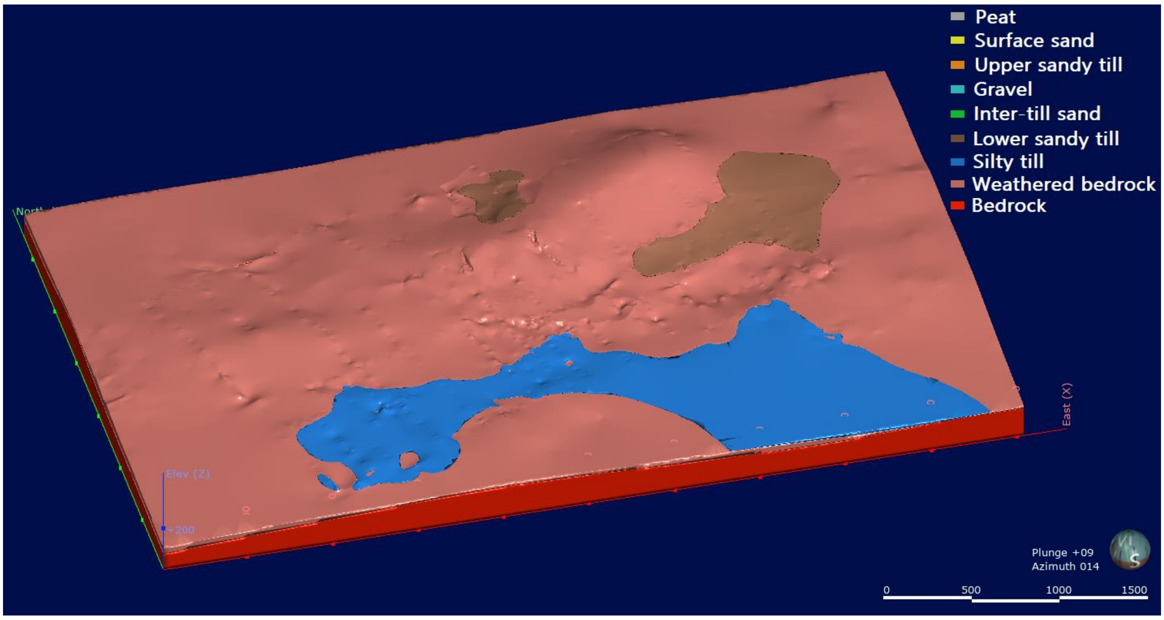

Figure 30: A view of the 3D model with all units overlying lower sandy till in the stratigraphy removed from view.

The inter-till sand in the model is present in limited areas on the southeastern and southern slopes of Kuusivaara (Figure 31). The unit does not outcrop anywhere in the model. The thickness of the unit varies mostly between 0.8 – 1.5 m in the larger, easternmost occurrence, and between 2 – 5 m in the westernmost, separate occurrence. The modelled unit is mostly based on three test pit observations of the unit, which account for the larger, easternmost occurrence in the model. Only a few contacts of the unit were found in the GPR interpretations in the easternmost part of the modelled unit. The westernmost part separated from the larger occurrence is based entirely on GPR interpretations.

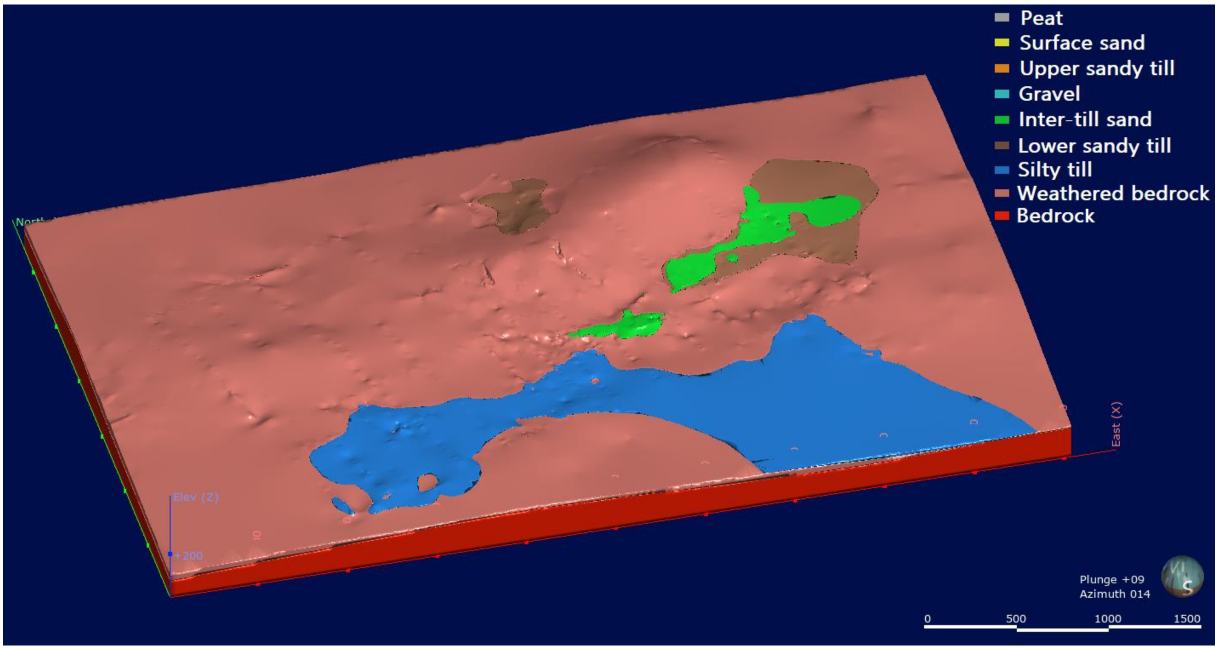

Figure 31: A view of the 3D model with all units overlying the inter-till sand in the stratigraphy removed from view.

The gravel in the model is present in limited areas in the northern slope and southern slope of Kuusivaara (Figure 32). The unit does not outcrop anywhere in the model. The thickness of the unit varies mostly between 1 – 2 m in the northern slope, and 0.5 – 3 m in the southern slope. The modelled occurrence in the northern slope is based on one test pit observation and GPR interpretations continuing from that test pit. The southern occurrences are based on one test pit observation and a few short contacts in the GPR interpretations.

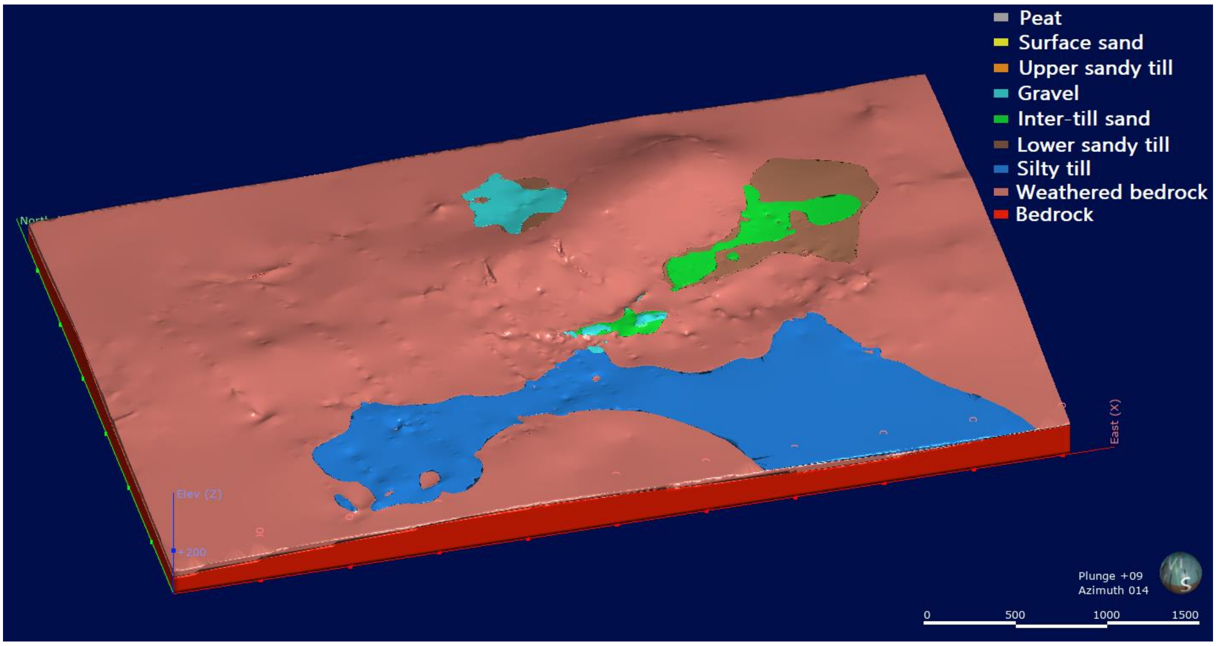

Figure 32: A view of the 3D model with all units overlying the gravel in the stratigraphy removed from view.

The upper sandy till in the model is present over all of the model area, except for small areas within the gorges in the upper parts of the Kuusivaara hill (Figure 33). The unit outcrops in the model on most of the model area, excluding mires and surface sand-covered areas. The thickness of the unit varies mostly between 1.5 – 3 m on the higher parts of Kuusivaara, 2 – 4 m on the lower slopes of Kuusivaara, and 1 – 5 m below peat in the mire areas. The modelled unit is based on observations in every test pit and soil drilling site used in the study as well as extensive coverage in the GPR interpretations.

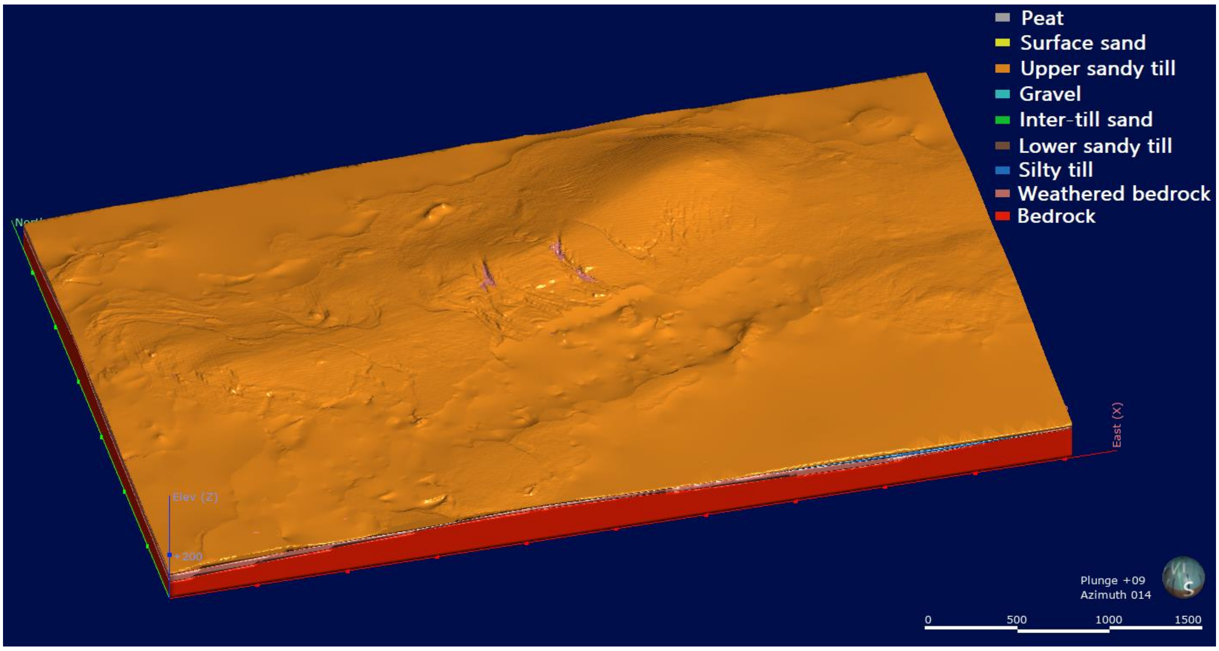

Figure 33: A view of the 3D model with all units overlying the upper sandy till in the stratigraphy removed from view.

The surface sand in the model is present in several, separate parts of the model area (Figure 34). The largest occurrence is below the peat on the mire area south of Kuusivaara, but there are several occurrences on the drylands as well. The unit outcrops in the model, where it is present outside the peat-covered areas. The thickness of the unit varies mostly between 1 – 2 m in the mire areas south of Kuusivaara, 0.5 – 2 m in the occurrences on drylands in the western parts of the model, 0.5 – 1.8 m in Pinoharju, and 0.5 – 1.5 m in the northeastern corner of the model. The modelled occurrences in the mire areas south of Kuusivaara are based on two test pit observations, one soil drilling observation and an extensive coverage of the GPR interpretations. The occurrences in the southwestern corner of the model are based almost entirely on the superficial deposits maps, with only one contact present in the GPR interpretations. The thickness in the southwestern corner was modelled to be similar to a test pit observation in the western part of the study area. The long zone of occurrences in the western edge of the model area are based on one test pit observation and the superficial deposits maps. The occurrence in Pinoharju is based on one test pit observation, and the occurrence in the northeastern slope of Kuusivaara is fully based on the superficial deposits maps.

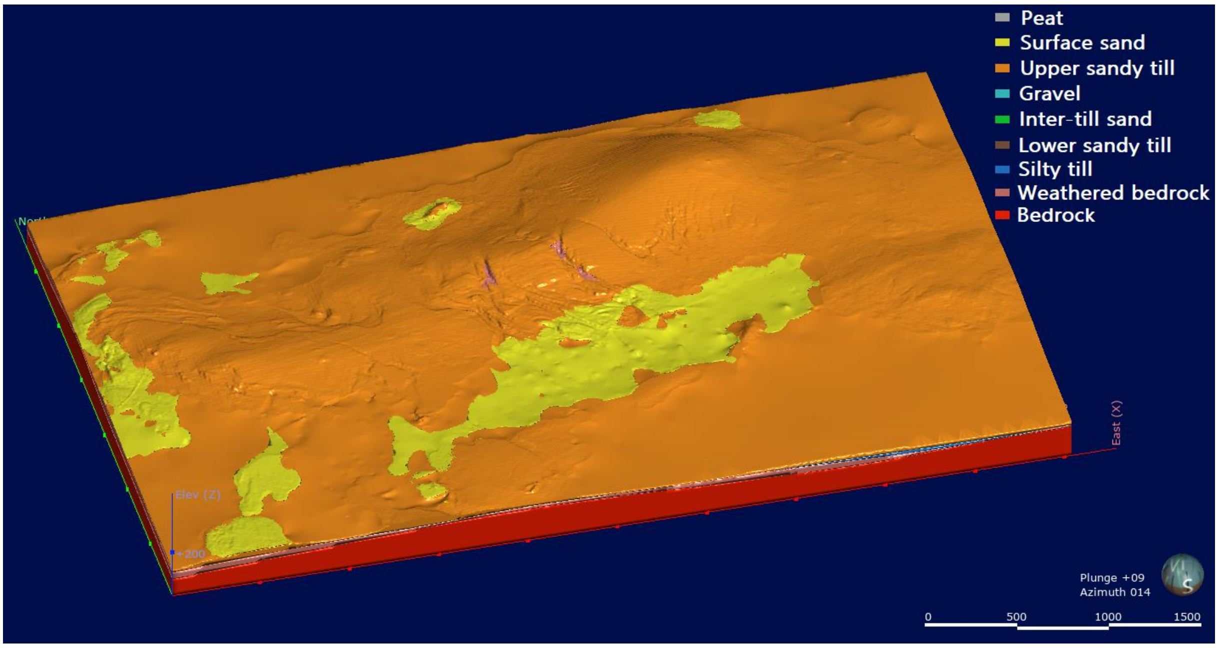

Figure 34: A view of the 3D model with all units overlying the surface sand in the stratigraphy removed from view.

The peat in the model is present in the wetlands surrounding Kuusivaara (Figure 35). The thickness of the unit varies greatly, with largest thicknesses in the modelled unit inside the study area ranging between 5 – 6 m. As peat is the topmost sediment in the framework stratigraphy used in the modelling, all occurrences of peat are on the surface of the model. The modelled unit in the mire areas south of Kuusivaara is based on soil drilling observations, peat coring observations and extensive coverage of the GPR interpretations. Elsewhere in the study area, the modelled unit is fully based on interpreted GPR contacts. The superficial deposit maps were used in all of the model area to place the borders between the peat cover and the drylands.

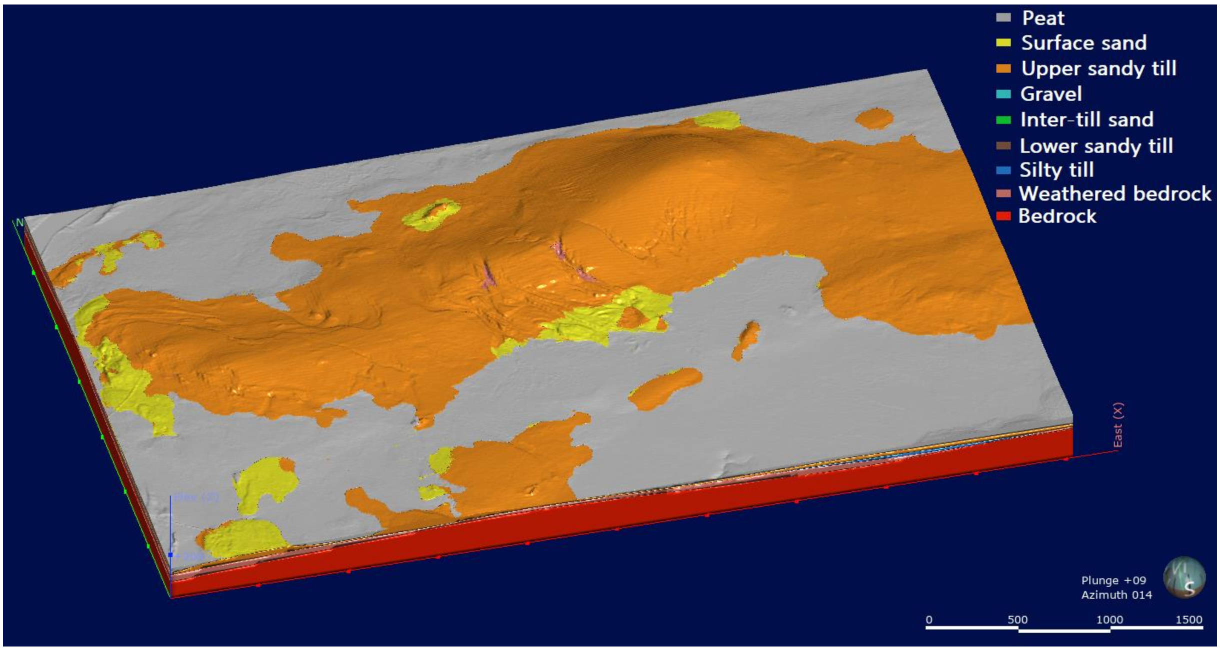

Figure 35: A view of the 3D model with all units in the stratigraphy present in the view.

To estimate the volumes of possibly extractable sediments in the modelled units, a cut-out of the model was created with both vertical and lateral limits (Figure 36). Vertically, the cut-out was set to include only the top three metres of the model (from the ground surface) to remove the deeper parts of the sediment cover, which are presumably situated below the groundwater level. Laterally, the cut-out was restricted to include only drylands part of the Kuusivaara hill and its extensions, based on the superficial deposits map, scale 1:20 000 (GTK, 2018). Additionally, the eastern extension of the Kuusivaara hill was limited to include only areas covered by the input data inside the study area, thus extracting the easternmost part of the drylands east of Kuusivaara.

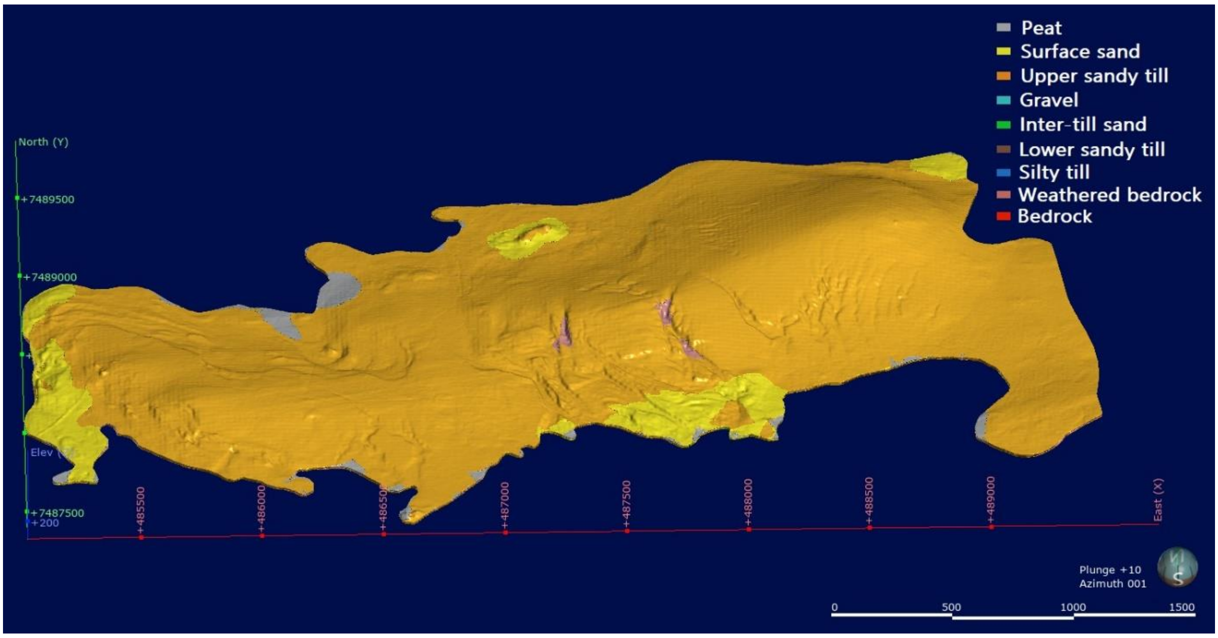

Figure 36: View of the cut-out of the 3D model including only top three metres of the model in the dryland areas of Kuusivaara and its extensions.

The volumes and surface areas of the sediment bodies in the cut-out were calculated automatically by the Leapfrog Geo software. The mass estimates (Table 6) were calculated with the cut-out volumes using the volume-to-mass conversion factors presented in Table 4.

Sorted sediments in the cut-out include parts of the modelled units surface sand, gravel and inter-till sand. The only sorted, modelled unit outcropping in the cut-out is surface sand. The surface sand bodies in the cut-out have following volumes and surface areas: the southern slopes of Kuusivaara volume 269 717 m^3 (surface area 341 072 m^2, mass estimate 490 885 – 525 948 metric tons (t)), the western flank of Kuusivaara 190 843 m^3 (377 322 m^2, 347 334 – 372 144 t), Pinoharju 28 710 m^3 (97 181 m^2, 52 252 – 55 985 t), and the northeastern edge of Kuusivaara 29 264 m^3 (69 882 m^2, 53 260 – 57 065 t).

The gravel bodies in the cut-out have following volumes and surface areas: the southern slopes of Kuusivaara volume 11 027 m^3 (surface area 31 379 m^2, mass estimate 24 259 – 24 700 t) and the northern slope of Kuusivaara 159 210 m^3 (386 080 m^2, 350 262 – 356 630 t). The inter-till sand bodies in the cut-out have following volumes and surface areas: the large occurrence in the southeastern slopes of Kuusivaara volume 68 806 m^3 (surface area 336 816 m^2, mass estimate 125 227 – 134 172 t) and the smaller, westernmost occurrence in the southern slopes of Kuusivaara 9 435 m^3 (33 438 m^2, 17 172 – 18 398 t).

All three till units of the framework stratigraphy are present in the cut-out. Silty till has small occurrences on the southern slopes of Kuusivaara close to the wetlands with a total volume of

3 212 m^3 (surface area 21 680 m^2, mass estimate 6 231 – 7 195 t). The lower sandy till bodies in the cut-out have following volumes and surface areas: the southeastern slopes of Kuusivaara volume 218 403 m^3 (surface area 776 928 m^2, mass estimate 399 677 – 489 223 t) and the northern slopes of Kuusivaara 57 423 m^3 (161 989 m^2, 105 084 – 128 628 t). The upper sandy till in the cut-out has a total volume of 13 056 000 m^3 (surface area 11 837 000 m^2, mass estimate 23 892 480 – 29 245 440 t).

Table 6: The volumes, surface areas and estimated masses of the sediment units in the cut-out of the 3D model.

Sediment unit and location	Volume (m^3)	Surface area (m^2)	Estimated mass (t)
Surface sand			
Southern slopes of Kuusivaara	269 717	341 072	490 885 – 525 948
Western flank of Kuusivaara	190 843	377 322	347 334 – 372 144
Pinoharju	28 710	97 181	52 252 – 55 985
Northeastern edge of Kuusivaara	29 264	69 882	53 260 – 57 065
Gravel			
Southern slopes of Kuusivaara	11 027	31 379	24 259 – 24 700
Northern slope of Kuusivaara	159 210	386 080	350 262 – 356 630
Inter-till sand			
Southeastern slope of Kuusivaara	68 806	336 816	125 227 – 134 172
Westernmost occurrence	9 435	33 438	17 172 – 18 398
Silty till			
Southern slopes of Kuusivaara	3 212	21 680	6 231 – 7 195
Lower sandy till			
Southeastern slope of Kuusivaara	218 403	776 928	399 677 – 489 223
Northern slope of Kuusivaara	57 423	161 989	105 084 – 128 628
Upper sandy till			
Kuusivaara	13 056 000	11 837 000	23 892 480 – 29 245 440

6.3 Geochemical results

6.3.1 Results of the grain-size fraction < 0.06 mm

The geochemical analysis results of the re-analysed percussion drilled till samples (Table 7) and recent test pit and soil drilling geochemical samples in the grain-size fraction < 0.06 mm (Table 8) are presented below. The combined geochemical results of both sample populations are presented in Table 9. The results are given separately for all sediment samples (weathered bedrock not included) and for each unit of the 3D model. The samples were placed into the units of the 3D model by examining the sampling location and depth in comparison with the 3D model. Only the elements controlled in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007) are presented, but it should be noted that these values are not as such comparable to the concentration limits of the decree, since the limits are set for concentrations analysed using the grain-size fraction < 2 mm.

Table 7: The geochemical results of the re-analysed drilled till samples in the grain-size fraction < 0.06 mm. The number of samples is given in parentheses in the Class column. All values are given in mg/kg. Class abbreviations: SEDI = all sediment samples, SS = surface sand, UST = upper sandy till, ST = silty till, WB = weathered bedrock.

Class	Sb	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	V	Zn
Median											
SEDI (90)	0.19	5.37	0.063	23.2	173.3	77.0	0.021	81.5	5.13	100.0	49.3
SS (2)	0.19	5.36	0.095	23.6	268.0	104.3	0.011	102.0	4.60	99.7	60.3
UST (85)	0.19	5.07	0.061	23.1	168.5	75.4	0.021	81.3	5.12	101.0	47.4
ST (3)	0.30	6.78	0.174	28.5	209.0	80.5	0.026	105.0	6.32	95.3	68.4
WB (13)	0.10	5.32	0.058	42.1	212.0	86.4	0.015	113.0	4.61	107.5	70.5
Mean											
SEDI (90)	0.20	5.68	0.105	24.3	188.8	116.6	0.021	87.6	5.26	99.0	50.9
SS (2)	0.19	5.36	0.095	23.6	268.0	104.3	0.011	102.0	4.60	99.7	60.3
UST (85)	0.20	5.62	0.103	24.3	186.1	118.3	0.022	86.6	5.24	99.0	50.1
ST (3)	0.27	7.34	0.151	23.4	211.7	75.4	0.022	104.7	6.14	97.8	67.3
WB (13)	0.12	7.01	0.159	37.9	257.9	185.2	0.019	135.4	10.73	115.1	72.2
Maximum											
SEDI (90)	0.58	14.80	1.465	55.6	702.0	1330	0.054	376.0	11.95	186.5	102.5
SS (2)	0.266	7.21	0.140	24.3	290.0	156.0	0.012	102.0	6.35	115.5	69.1
UST (85)	0.58	14.80	1.465	55.6	702.0	1330	0.054	376.0	11.95	186.5	102.5
ST (3)	0.33	9.49	0.195	29.7	217.0	88.1	0.031	105.5	7.22	104.0	76.6
WB (13)	0.32	22.2	0.93	53.2	987.0	1020	0.069	406.0	52.40	178.5	125.5

Table 8: The geochemical results of the recent geochemical samples from test pits and soil drilling in the grain-size fraction < 0.06 mm. The number of samples is given in parentheses in the Class column. All values are given in mg/kg. Class abbreviations: SEDI = all sediment samples, SS = surface sand, UST = upper sandy till, GR = gravel, IS = inter-till sand, LST = lower sandy till, ST = silty till, WB = weathered bedrock.

Class	Sb	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	V	Zn
Median											
SEDI (45)	0.16	4.94	0.072	19.5	156.5	56.6	0.020	67.8	4.43	87.5	42.4
SS (1)	0.072	3.11	0.059	12.4	103.0	26.3	0.009	38.7	2.39	52.5	24.8
UST (35)	0.15	4.73	0.059	19.5	153.0	56.5	0.020	67.3	4.43	87.9	40.4
GR (2)	0.17	11.20	0.112	39.0	208.5	46.8	0.049	60.9	5.24	86.0	6.3
IS (1)	0.19	7.91	0.065	19.0	168.0	50.6	0.040	70.1	6.16	110.0	40.4
LST (2)	0.18	6.82	0.094	16.1	177.8	52.5	0.024	70.2	4.60	80.6	41.3
ST (4)	0.13	3.54	0.131	32.3	187.5	99.1	0.012	96.1	4.22	83.3	85.3
WB (8)	0.05	1.86	0.043	42.9	151.5	248.5	0.005	123.0	2.23	188.5	75.7
Mean											
SEDI (45)	0.18	5.32	0.097	21.7	172.1	72.1	0.021	79.9	5.36	89.2	46.1
SS (1)	0.072	3.11	0.059	12.4	103.0	26.3	0.009	38.7	2.39	52.5	24.8
UST (35)	0.19	4.96	0.074	19.5	163.4	73.3	0.020	70.0	4.57	91.8	43.2
GR (2)	0.17	11.20	0.112	39.0	208.5	46.8	0.049	60.9	5.24	86.0	6.3
IS (1)	0.19	7.91	0.065	19.0	168.0	50.6	0.040	70.1	6.16	110.0	40.4
LST (2)	0.18	6.82	0.094	16.1	177.8	52.5	0.024	70.2	4.60	80.6	41.3
ST (4)	0.13	4.71	0.315	37.6	245.2	100.9	0.014	193.6	13.25	76.3	81.9
WB (8)	0.05	1.88	0.071	45.0	203.2	206.7	0.006	115.1	2.52	192.4	72.0
Maximum											
SEDI (45)	0.34	15.15	0.973	63.9	585.0	219.0	0.079	550.0	41.20	179.0	98.3
SS (1)	0.072	3.11	0.059	12.4	103.0	26.3	0.009	38.7	2.39	52.5	24.8
UST (35)	0.34	10.30	0.189	32.2	308.0	219.0	0.040	146.5	7.21	179.0	69.9
GR (2)	0.17	15.15	0.149	61.6	215.0	61.8	0.079	70.2	6.85	90.6	8.0
IS (1)	0.19	7.91	0.065	19.0	168.0	50.6	0.040	70.1	6.16	110.0	40.4
LST (2)	0.27	10.40	0.114	20.7	236.0	65.2	0.025	95.5	5.33	98.5	52.9
ST (4)	0.23	10.65	0.973	63.9	585.0	147.0	0.027	550.0	41.20	122.0	98.3
WB (8)	0.11	3.37	0.231	55.8	635.0	336.0	0.012	186.5	5.27	268.0	89.5

Table 9: The geochemical results of the combined sample populations of the re-analysed drilled till samples and recent test pit and soil drilling geochemical samples in the grain-size fraction < 0.06 mm. The number of samples is given in parentheses in the Class column. All values are given in mg/kg. Class abbreviations: SEDI = all sediment samples, SS = surface sand, UST = upper sandy till, GR = gravel, IS = inter-till sand, LST = lower sandy till, ST = silty till, WB = weathered bedrock.

Class	Sb	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	V	Zn
Median											
SEDI (135)	0.17	5.07	0.064	21.9	168.0	68.3	0.021	75.2	4.92	94.6	46.4
SS (3)	0.10	3.51	0.059	22.8	246.0	52.5	0.009	102	2.84	83.8	51.5
UST (120)	0.18	5.00	0.061	21.8	165.0	69.2	0.021	75.2	4.90	95.6	45.1
GR (2)	0.17	11.20	0.112	39.0	208.5	46.8	0.049	60.9	5.24	86.0	6.3
IS (1)	0.19	7.91	0.065	19.0	168.0	50.6	0.040	70.1	6.16	110.0	40.4
LST (2)	0.18	6.82	0.094	16.1	177.8	52.5	0.024	70.2	4.60	80.6	41.3
ST (7)	0.20	5.89	0.134	29.7	209.0	80.5	0.014	105.0	4.96	94.0	72.8
WB (21)	0.07	2.55	0.055	42.1	184.5	100.0	0.011	114.0	3.83	148.5	73.6
Mean											
SEDI (135)	0.19	5.56	0.102	23.5	183.2	101.7	0.021	85.0	5.29	95.8	49.3
SS (3)	0.15	4.61	0.083	19.8	213.0	78.3	0.010	80.9	3.86	83.9	48.5
UST (120)	0.19	5.43	0.095	22.9	179.5	105.2	0.021	81.8	5.05	96.9	48.1
GR (2)	0.17	11.20	0.112	39.0	208.5	46.8	0.049	60.9	5.24	86.0	6.3
IS (1)	0.19	7.91	0.065	19.0	168.0	50.6	0.040	70.1	6.16	110.0	40.4
LST (2)	0.18	6.82	0.094	16.1	177.8	52.5	0.024	70.2	4.60	80.6	41.3
ST (7)	0.19	5.84	0.244	32.8	230.8	90.0	0.017	155.5	10.20	85.5	75.6
WB (21)	0.10	5.05	0.125	40.6	237.1	193.4	0.014	127.6	7.60	144.5	72.1
Maximum											
SEDI (135)	0.58	15.15	1.465	63.9	702.0	1330	0.079	550	41.20	186.5	102.5
SS (3)	0.27	7.21	0.140	24.3	290.0	156	0.012	102	6.35	115.5	69.1
UST (120)	0.58	14.80	1.465	55.6	702.0	1330	0.054	376	11.95	186.5	102.5
GR (2)	0.17	15.15	0.149	61.6	215.0	61.8	0.079	70.2	6.85	90.6	8.0
IS (1)	0.19	7.91	0.065	19.0	168.0	50.6	0.040	70.1	6.16	110.0	40.4
LST (2)	0.27	10.40	0.114	20.7	236.0	65.2	0.025	95.5	5.33	98.5	52.9
ST (7)	0.33	10.65	0.973	63.9	585.0	147.0	0.031	550.0	41.20	122.0	98.3
WB (21)	0.32	22.20	0.930	55.8	987.0	1020	0.069	406.0	52.40	268.0	125.5

Three duplicate geochemical samples were taken from the test pits in August 2020 with identical methodology, sampling location and sample depth. The geochemical analysis results of those duplicate samples in the grain-size fraction < 0.06 mm are presented in Table 10. Only the elements controlled in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007) are presented.

Table 10: The geochemical results of the three test pit duplicate samples in the grain-size fraction < 0.06 mm. Sample ID ending 'R' refers to a duplicate. All values are given in mg/kg.

Sample ID	Sb	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	V	Zn
20TR021.2	0.24	4.59	0.103	18.9	138.0	56.5	0.030	69.1	4.85	81.7	51.1
20TR021.2R	0.25	5.19	0.100	17.7	131.0	57.4	0.021	70.5	5.34	81.2	52.0
20TR025.2	0.28	10.30	0.092	21.5	213.0	89.4	0.023	97.1	4.27	106.5	60.1
20TR025.2R	0.29	10.15	0.092	22.1	221.0	86.9	0.024	99.9	5.42	105.5	59.7
20TR028.1	0.12	3.48	0.040	19.0	132.5	163.5	0.019	59.2	4.41	92.9	36.6
20TR028.1R	0.11	2.74	0.033	17.0	117.5	148.5	0.017	51.8	3.87	83.1	33.0

6.3.2 Results of the grain-size fraction < 2 mm

The geochemical analysis results of the recent test pit and soil drilling geochemical samples in the grain-size fraction < 2 mm are presented in Table 11. The results are given separately for all sediment samples (weathered bedrock not included) and for each unit of the 3D model. Only the elements controlled in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007) are presented.

Table 11: The geochemical results of the recent test pit and soil drilling geochemical samples in the grain-size fraction < 2 mm. The number of samples is given in parentheses in the Class column. All values are given in mg/kg. Bolded values exceed the threshold limit (214/2007) or recommended background concentration value (Cr, Ni). Class abbreviations: Limit = threshold limit (214/2007) or recommended background concentration value (Cr, Ni), SEDI = all sediment samples, SS = surface sand, UST = upper sandy till, GR = gravel, IS = inter-till sand, LST = lower sandy till, ST = silty till, WB = weathered bedrock.

Class	Sb	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	V	Zn
Limit	2	5	1	20	162	100	0.5	61	60	100	200
Median											
SEDI (45)	0.09	2.28	0.043	10.8	79.0	26.0	0.014	37.1	2.55	50.0	22.6
SS (1)	0.04	1.69	0.039	7.7	43.0	15.7	0.010	23.2	1.68	33.5	18.9
UST (35)	0.09	2.28	0.039	10.8	79.0	26.0	0.015	37.0	2.57	52.1	22.2
GR (2)	0.09	2.29	0.046	9.8	83.2	16.4	0.011	37.6	1.92	45.5	22.0
IS (1)	0.08	2.33	0.037	7.9	51.3	16.9	0.015	21.9	2.18	39.0	15.3
LST (2)	0.13	3.77	0.063	12.0	112.8	27.4	0.015	45.2	3.18	54.9	25.8
ST (4)	0.08	3.28	0.087	**26.3**	148.5	67.3	0.013	**86.1**	2.86	65.7	57.2
WB (8)	0.04	1.38	0.051	**42.7**	152.3	**209.8**	0.008	**123.3**	2.20	**165.0**	66.4
Mean											
SEDI (45)	0.10	2.76	0.063	12.5	96.4	38.3	0.014	47.6	3.27	56.2	27.7
SS (1)	0.04	1.69	0.039	7.7	43.0	15.7	0.010	23.2	1.68	33.5	18.9
UST (35)	0.11	2.72	0.047	11.4	88.5	36.5	0.015	40.3	2.73	56.4	23.7
GR (2)	0.09	2.29	0.046	9.8	83.2	16.4	0.011	37.6	1.92	45.5	22.0
IS (1)	0.08	2.33	0.037	7.9	51.3	16.9	0.015	21.9	2.18	39.0	15.3
LST (2)	0.13	3.77	0.063	12.0	112.8	27.4	0.015	45.2	3.18	54.9	25.8
ST (4)	0.08	3.24	0.219	**26.2**	**188.3**	80.9	0.013	**130.2**	9.35	70.5	72.2
WB (8)	0.04	1.40	0.072	**40.0**	**198.4**	**195.8**	0.009	**117.7**	2.19	**168.2**	64.9
Maximum											
SEDI (45)	0.22	**7.09**	0.685	**35.5**	**431.0**	**163.0**	0.029	**325.0**	29.40	**142.0**	136.5
SS (1)	0.04	1.69	0.039	7.7	43.0	15.7	0.010	23.2	1.68	33.5	18.9
UST (35)	0.22	**7.09**	0.106	**22.6**	**199.5**	**163.0**	0.029	**97.9**	4.87	**142.0**	42.2
GR (2)	0.09	2.32	0.046	10.7	91.2	16.6	0.011	37.7	1.93	49.0	23.2
IS (1)	0.08	2.33	0.037	7.9	51.3	16.9	0.015	21.9	2.18	39.0	15.3
LST (2)	0.20	**6.01**	0.083	18.0	158.5	38.9	0.019	**66.4**	4.12	66.0	36.0
ST (4)	0.12	**5.60**	0.685	**35.5**	**431.0**	**155.5**	0.017	**325.0**	29.40	**135.5**	136.5
WB (8)	0.11	2.48	0.214	**56.9**	**607.0**	**402.0**	0.021	**209.0**	4.69	**298.0**	89.0

The geochemical analysis results of the test pit duplicate samples in the grain-size fraction < 2 mm are presented in Table 12. Only the elements controlled in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007) are presented.

Table 12: The geochemical results of the three test pit duplicate samples in the grain-size fraction < 2 mm. Sample ID ending 'R' refers to a duplicate. All values are given in mg/kg.

Sample ID	Sb	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	V	Zn
20TR021.2	0.14	2.87	0.066	12.2	70.3	28.3	0.016	37.1	2.93	54.1	25.0
20TR021.2R	0.14	3.11	0.066	12.8	70.2	29.4	0.017	37.2	3.23	53.3	25.1
20TR025.2	0.21	7.09	0.074	21.1	154.5	59.8	0.021	74.0	4.01	81.3	40.3
20TR025.2R	0.22	6.64	0.073	21.1	156.5	55.8	0.021	75.2	4.87	79.6	37.7
20TR028.1	0.08	1.87	0.029	11.0	76.8	66.2	0.015	30.3	2.58	53.7	19.7
20TR028.1R	0.05	1.44	0.027	10.1	70.0	60.7	0.011	26.4	2.33	49.1	18.3

6.3.3 Results of the converted grain-size fraction < 2 mm

The geochemical results of the re-analysed drilled till samples in the grain-size fraction < 0.06 mm were converted into comparable results to concentrations analysed in the grain-size fraction < 2 mm, as described in *5.2.3 Geochemical analyses*. The conversion factors, which were calculated using analysis results of the recent test pit and soil drilling samples, are presented in Table 13.

Table 13: The conversion factors used to convert the concentrations analysed from the grain-size fraction < 0.06 mm to concentrations comparable to the grain-size fraction < 2 mm. The number of samples, which the conversion factors were calculated with, are given in parentheses in the Class column.

Class	Sb	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	V	Zn
Sediments (45)	0.544	0.537	0.660	0.563	0.536	0.501	0.769	0.544	0.596	0.609	0.548
Weathered bedrock (8)	0.806	0.762	1.100	0.914	0.982	0.883	1.333	0.951	0.899	0.873	0.986

The converted concentrations of the re-analysed drilled till samples comparable to the grain-size fraction < 2 mm are presented in Table 14. The results are given separately for all sediment samples (weathered bedrock not included) and for each unit of the 3D model. Only the elements controlled in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007) are presented.

Table 14: The converted geochemical results of the re-analysed drilled till samples comparable to the fraction < 2 mm. The number of samples is given in parentheses in the Class column. All values are given in mg/kg. Bolded values exceed the threshold limit (214/2007) or recommended background concentration value (Cr, Ni). Class abbreviations: Limit = threshold limit (214/2007) or recommended background concentration value (Cr, Ni), SEDI = all sediment samples, SS = surface sand, UST = upper sandy till, ST = silty till, WB = weathered bedrock.

Class	Sb	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	V	Zn
Limit	2	5	1	20	162	100	0.5	61	60	100	200
Median											
SEDI (90)	0.10	2.89	0.041	13.0	92.8	38.5	0.016	44.3	3.06	60.9	27.0
SS (2)	0.10	2.88	0.062	13.2	143.6	52.2	0.008	55.4	2.74	60.7	33.0
UST (85)	0.10	2.72	0.040	13.0	90.3	37.8	0.016	44.2	3.05	61.5	26.0
ST (3)	0.16	3.64	0.115	16.0	112.0	40.3	0.020	57.1	3.77	58.0	37.5
WB (13)	0.08	4.06	0.064	**38.5**	**208.1**	76.3	0.020	**107.5**	4.14	93.9	69.5
Mean											
SEDI (90)	0.11	3.05	0.069	13.7	101.2	58.4	0.016	47.6	3.13	60.3	27.9
SS (2)	0.10	2.88	0.062	13.2	143.6	52.2	0.008	55.4	2.74	60.7	33.0
UST (85)	0.11	3.02	0.068	13.7	99.7	59.3	0.017	47.1	3.12	60.3	27.4
ST (3)	0.15	3.94	0.100	14.8	113.4	37.8	0.017	56.9	3.66	59.5	36.8
WB (13)	0.10	**5.35**	0.175	**34.6**	**253.2**	**163.6**	0.026	**128.8**	9.65	**100.5**	71.1
Maximum											
SEDI (90)	0.32	**7.95**	0.967	**31.3**	**376.2**	**666.2**	0.042	**204.4**	7.13	**113.5**	56.1
SS (2)	0.14	3.87	0.092	13.7	155.4	78.1	0.009	55.4	3.79	70.3	37.8
UST (85)	0.32	**7.95**	0.967	**31.3**	**376.2**	**666.2**	0.042	**204.4**	7.13	**113.5**	56.1
ST (3)	0.18	**5.10**	0.129	16.7	116.3	44.1	0.024	57.3	4.31	63.3	41.9
WB (13)	0.26	**16.92**	**1.023**	**48.6**	**968.9**	**901.0**	0.092	**386.2**	47.11	**155.9**	123.7

6.3.4 Combined results of the grain-size fraction < 2 mm

The combined results with the converted concentrations of the re-analysed drilled till samples comparable to the grain-size fraction < 2 mm and recent test pit and soil drilling geochemical samples in the grain-size fraction < 2 mm are presented in Table 15. The results are given separately for all sediment samples (weathered bedrock not included) and for each unit of the 3D model. Only the elements controlled in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007) are presented.

Table 15: Results of the combined sample populations of the converted concentrations of the re-analysed drilled till samples and the recent test pit and soil drilling geochemical samples in the grain-size fraction < 2 mm. The number of samples is given in parentheses in the Class column. All values are given in mg/kg. Bolded values exceed the threshold limit (214/2007) or recommended background concentration value (Cr, Ni). Class abbreviations: Limit = threshold limit (214/2007) or recommended background concentration value (Cr, Ni), SEDI = all sediment samples, SS = surface sand, UST = upper sandy till, GR = gravel, IS = inter-till sand, LST = lower sandy till, ST = silty till, WB = weathered bedrock.

Class	Sb	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	V	Zn
Limit	2	5	1	20	162	100	0.5	61	60	100	200
Median											
SEDI (135)	0.09	2.67	0.042	12.6	88.4	34.7	0.015	41.5	2.88	57.2	25.0
SS (3)	0.06	1.89	0.039	12.8	131.8	26.3	0.009	55.4	1.69	51.0	28.2
UST (120)	0.10	2.69	0.040	12.5	86.5	34.8	0.016	41.2	2.89	57.2	24.5
GR (2)	0.09	2.29	0.046	9.8	83.2	16.4	0.011	37.6	1.92	45.5	22.0
IS (1)	0.08	2.33	0.037	7.9	51.3	16.9	0.015	21.9	2.18	39.0	15.3
LST (2)	0.13	3.77	0.063	12.0	112.8	27.4	0.015	45.2	3.18	54.9	25.8
ST (7)	0.11	3.64	0.093	16.7	112.0	40.3	0.014	57.1	3.39	63.3	41.9
WB (21)	0.05	1.94	0.061	**40.4**	**169.5**	88.3	0.016	**110.5**	3.20	**110.9**	69.5
Mean											
SEDI (135)	0.11	2.95	0.067	13.3	99.6	51.7	0.015	47.6	3.18	58.9	27.8
SS (3)	0.08	2.48	0.055	11.4	110.1	40.0	0.009	44.7	2.39	51.6	28.3
UST (120)	0.11	2.93	0.062	13.0	96.5	52.6	0.016	45.1	3.01	59.2	26.3
GR (2)	0.09	2.29	0.046	9.8	83.2	16.4	0.011	37.6	1.92	45.5	22.0
IS (1)	0.08	2.33	0.037	7.9	51.3	16.9	0.015	21.9	2.18	39.0	15.3
LST (2)	0.13	3.77	0.063	12.0	112.8	27.4	0.015	45.2	3.18	54.9	25.8
ST (7)	0.11	3.54	0.168	**21.3**	156.2	62.4	0.014	**98.8**	6.91	65.8	57.0
WB (21)	0.08	3.84	0.136	**36.6**	**232.3**	**175.8**	0.020	**124.6**	6.81	**126.3**	68.7
Maximum											
SEDI (135)	0.32	**7.95**	0.967	**35.5**	**431.0**	**666.2**	0.062	**325.0**	29.40	**142.0**	136.5
SS (3)	0.14	3.87	0.092	13.7	155.4	78.1	0.010	55.4	3.79	70.3	37.8
UST (120)	0.32	**7.95**	0.967	**31.3**	**376.2**	**666.2**	0.042	**204.4**	7.13	**142.0**	56.1
GR (2)	0.09	2.32	0.046	10.7	91.2	16.6	0.011	37.7	1.93	49.0	23.2
IS (1)	0.08	2.33	0.037	7.9	51.3	16.9	0.015	21.9	2.18	39.0	15.3
LST (2)	0.20	**6.01**	0.083	18.0	158.5	38.9	0.019	**66.4**	4.12	66.0	36.0
ST (7)	0.18	**5.60**	0.685	**35.5**	**431.0**	**155.5**	0.024	**325.0**	29.40	**135.5**	136.5
WB (21)	0.26	**16.92**	**1.023**	**56.9**	**968.9**	**901.0**	0.092	**386.2**	47.11	**298.0**	123.7

6.3.5 Solubility test results of the sediment samples

The results of the two-step batch leaching test performed on eighteen sediment samples are presented in Table 16. The sediment samples were collected from the test pits excavated in August 2020. Twelve of the samples were from the upper sandy till, which was also the only sediment unit to be tested with more samples than one or two. The results are given separately for all sediment samples combined and for each unit of the 3D model. The results are comparable to the limits set in the Government Decree on changing the Government Decision on Landfills (202/2006), and only the elements and parameters set in the decree are presented in the results.

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Table 16: The results of the two-step batch leaching test with liquid-to-solid ratio of 10. The number of samples is given in parentheses in the Class column. All values are given in mg/kg (dry weight) and values below detection limit are presented as the detection limit. Bolded values exceed the upper limit set for stable waste in legislation (202/2006). Class abbreviations: Limit = upper limit set for stable waste (202/2006), All = all sediment samples, SS = surface sand, UST = upper sandy till, GR = gravel, IS = inter-till sand, LST = lower sandy till, ST = silty till.

Class	DOC	Phenol Index	Cl^-	F^-	TDS	SO_4^{2-}	As	Ba	Cd	Cr_{tot}	Cu	Hg	Mo	Ni	Pb	Sb	Se	Zn
Limit	500	1	800	10	4000	1000	0.5	20	0.04	0.5	2	0.01	0.5	0.4	0.5	0.06	0.1	4
Median																		
All (18)	33.3	0.050	10.6	0.50	440	7.3	0.010	0.28	0.005	0.078	0.055	0.0001	0.018	0.044	0.010	0.010	0.050	0.254
SS (1)	14.9	0.050	9.8	0.32	270	5.9	0.010	0.45	0.005	0.050	0.012	0.0001	0.010	0.030	0.010	0.010	0.050	0.183
UST (12)	40.5	0.050	11.8	0.50	541	8.2	0.011	0.228	0.005	0.078	0.066	0.0001	0.018	0.048	0.012	0.010	0.050	0.210
GR (1)	23.0	0.050	9.1	0.47	263	5.0	0.010	0.433	0.005	0.050	0.011	0.0001	0.010	0.030	0.010	0.010	0.050	0.314
IS (1)	40.0	0.050	6.5	1.76	2340	13.2	0.044	0.858	0.005	**0.684**	0.295	0.0001	0.034	**0.434**	0.042	0.010	0.050	0.291
LST (2)	45.2	0.050	7.0	0.27	1140	13.2	0.018	0.374	0.005	0.261	0.308	0.0003	0.025	0.132	0.024	0.010	0.050	0.157
ST (1)	20.4	0.050	16.5	1.88	2070	5.9	0.034	0.758	0.005	**1.830**	0.531	0.0009	0.025	**0.570**	0.071	0.010	0.050	0.761
Maximum																		
All (18)	109.0	0.050	22.2	1.88	**5510**	16.3	0.044	0.858	0.005	**1.830**	0.531	0.0009	0.058	**0.570**	0.071	0.010	0.050	0.896
SS (1)	14.9	0.050	9.8	0.32	270	5.9	0.010	0.45	0.005	0.050	0.012	0.0001	0.010	0.030	0.010	0.010	0.050	0.183
UST (12)	109.0	0.050	22.2	1.70	**5510**	16.3	0.042	0.657	0.005	**0.596**	0.308	0.0004	0.058	0.225	0.057	0.010	0.050	0.896
GR (1)	23.0	0.050	9.1	0.47	263	5.0	0.01	0.433	0.005	0.050	0.011	0.0001	0.010	0.030	0.010	0.010	0.050	0.314
IS (1)	40.0	0.050	6.5	1.76	2340	13.2	0.044	0.858	0.005	**0.684**	0.295	0.0001	0.034	**0.434**	0.042	0.010	0.050	0.291
LST (2)	44.0	0.050	10.4	0.88	545	6.6	0.010	0.168	0.005	0.213	0.051	0.0002	0.043	0.059	0.011	0.010	0.050	0.331
ST (1)	20.4	0.050	16.5	1.88	2070	5.9	0.034	0.758	0.005	**1.830**	0.531	0.0009	0.025	**0.570**	0.071	0.010	0.050	0.761

6.4 Slug test results

Slug tests were performed in eight groundwater wells in Kuusivaara between the 7th and 10th of July 2020 (Figure 37). Three of the wells were situated north of the water shed on the crest of Kuusivaara, and five wells were south of the water shed.

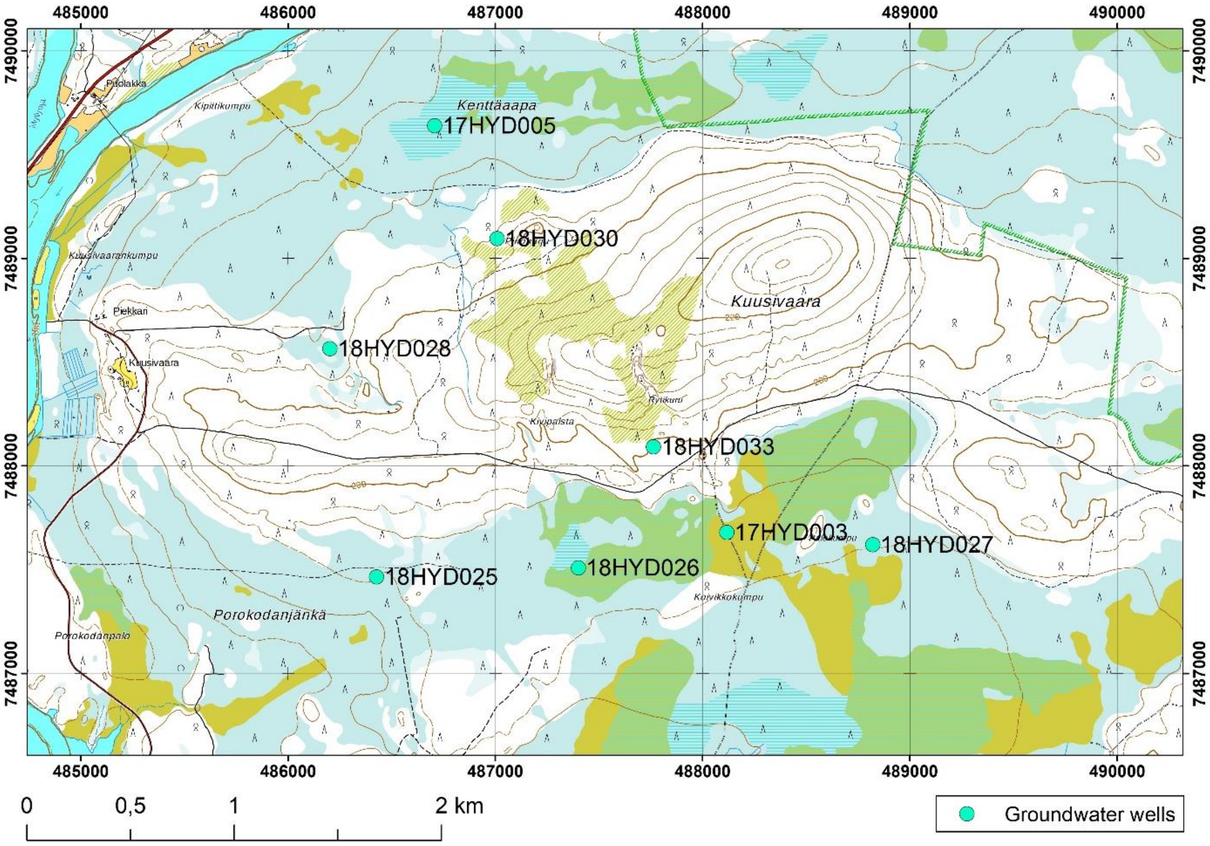

Figure 37: Locations of the groundwater wells in which the slug tests were performed. Background map by National Land Survey of Finland.

The results from the slug tests performed are summarised in Table 17. Data from 20 individual tests was analysed. Fourteen of the tests were falling-head tests and six rising-head tests. The calculated water permeability (K) values ranged from $1.30 \cdot 10^{-7}$ to $6.30 \cdot 10^{-5}$ m/s.

Table 17: The summarised results of the slug tests. The screened geological unit is given with the names used in the 3D model, abbreviations: P = peat, IS = inter-till sand, UST = upper sandy till, SS = surface sand, and WB = weathered bedrock.

Well ID	No. of tests	Rising-head	Falling-head	Mean K [m/s]	Min. K [m/s]	Max. K [m/s]	Screened unit
17HYD003	2		X	$2.60 \cdot 10^{-6}$	$2.30 \cdot 10^{-6}$	$2.90 \cdot 10^{-6}$	P, IS, UST
17HYD005	2		X	$5.60 \cdot 10^{-5}$	$4.90 \cdot 10^{-5}$	$6.30 \cdot 10^{-5}$	SS, UST
18HYD025	4	X	X	$1.02 \cdot 10^{-5}$	$6.60 \cdot 10^{-6}$	$1.40 \cdot 10^{-5}$	UST
18HYD026	2		X	$1.45 \cdot 10^{-7}$	$1.30 \cdot 10^{-7}$	$1.60 \cdot 10^{-7}$	P, UST
18HYD027	2	X		$1.65 \cdot 10^{-5}$	$1.60 \cdot 10^{-5}$	$1.70 \cdot 10^{-5}$	UST
18HYD028	2		X	$1.20 \cdot 10^{-5}$	$1.20 \cdot 10^{-5}$	$1.20 \cdot 10^{-5}$	WB
18HYD030	4	X	X	$4.50 \cdot 10^{-6}$	$2.10 \cdot 10^{-6}$	$8.50 \cdot 10^{-6}$	WB
18HYD033	2		X	$5.10 \cdot 10^{-6}$	$4.40 \cdot 10^{-6}$	$5.80 \cdot 10^{-6}$	WB

6.5 Water permeability results based on the grain-size distributions

The grain-size distribution of 27 samples was determined in the laboratory and the water permeability results calculated using the grain-size distributions are presented in Table 18. The results are given separately for each of the sediment units of the 3D model.

Table 18: A summary of the water permeability values (m/s) calculated with Sauerbrei (S) and Kozeny-Carman (K-C) methods using the grain-size distributions of sediment samples. The number of samples is given in parentheses in the class column. Sediment unit abbreviations: SS = surface sand, UST = upper sandy till, GR = gravel, IS = inter-till sand, LST = lower sandy till, ST = silty till.

Sediment unit	Mean S	Mean K-C	Median S	Median K-C	Min. S	Min. K-C	Max. S	Max. K-C
SS (1)	$2.11 \cdot 10^{-3}$	$2.69 \cdot 10^{-3}$	$2.11 \cdot 10^{-3}$	$2.69 \cdot 10^{-3}$	$2.11 \cdot 10^{-3}$	$2.69 \cdot 10^{-3}$	$2.11 \cdot 10^{-3}$	$2.69 \cdot 10^{-3}$
UST (19)	$1.03 \cdot 10^{-2}$	$8.03 \cdot 10^{-3}$	$2.69 \cdot 10^{-4}$	$5.17 \cdot 10^{-5}$	$2.11 \cdot 10^{-5}$	$1.02 \cdot 10^{-5}$	$1.55 \cdot 10^{-1}$	$1.47 \cdot 10^{-1}$
GR (3)	$6.11 \cdot 10^{-2}$	$4.19 \cdot 10^{-2}$	$5.27 \cdot 10^{-2}$	$5.74 \cdot 10^{-2}$	$9.69 \cdot 10^{-3}$	$1.08 \cdot 10^{-2}$	$1.21 \cdot 10^{-1}$	$5.74 \cdot 10^{-2}$
IS (1)	$1.71 \cdot 10^{-3}$	$6.38 \cdot 10^{-5}$	$1.71 \cdot 10^{-3}$	$6.38 \cdot 10^{-5}$	$1.71 \cdot 10^{-3}$	$6.38 \cdot 10^{-5}$	$1.71 \cdot 10^{-3}$	$6.38 \cdot 10^{-5}$
LST (1)	$1.24 \cdot 10^{-4}$	$2.69 \cdot 10^{-5}$	$1.24 \cdot 10^{-4}$	$2.69 \cdot 10^{-5}$	$1.24 \cdot 10^{-4}$	$2.69 \cdot 10^{-5}$	$1.24 \cdot 10^{-4}$	$2.69 \cdot 10^{-5}$
ST (2)	$1.96 \cdot 10^{-5}$	$6.78 \cdot 10^{-6}$	$1.96 \cdot 10^{-5}$	$6.78 \cdot 10^{-6}$	$1.82 \cdot 10^{-5}$	$5.74 \cdot 10^{-6}$	$2.11 \cdot 10^{-5}$	$7.81 \cdot 10^{-6}$

7 Discussion

7.1 The 3D model and sediment masses

As mentioned above, the input data of the 3D model was not sufficient outside the study area presented in Figure 26, and as such the model cannot be regarded as reliable in those areas. Inside the study area, the area on the southern slope of Kuusivaara showing signs of mass-flows could not either be reliably modelled with the input data used in the modelling. The available *in situ* data on that area shows a complex stratigraphy with tills, mass-flow diamictons and several sorted sediment units. Based on the hillshade LiDAR image, the complex stratigraphy may have resulted from mass-flows and alluvial processes acting in the drainage channels south of the crest of Kuusivaara.

Considering the different units of the 3D model, five of them had a good coverage in the interpreted GPR contacts: peat, surface sand, upper sandy till, weathered bedrock and bedrock. However, the sorted sediment units in between tills as well as the till units below upper sandy till could not be recognized extensively in the GPR interpretations. The modelled layers of those units were mostly based on continuing the *in situ* observations with geological and geomorphological interpretations. This entails a larger margin of error with both the presence and thickness of the units in the model. For example, it is uncertain whether the inter-till sand and lower sandy till units continue outwards from the southeastern part of Kuusivaara where they have been observed in test pits.

In the results of the 3D model cut-out, volumes, surface areas and mass estimates were given for separate bodies of the sorted sediment units (surface sand, gravel, inter-till sand). For all the listed volumes (in m^3), the corresponding surface areas (in m^2) can be seen to be significantly larger, generally in the range that the surface areas are more than two times the volumes. This shows that the sorted sediments are generally present in the cut-out model as thin layers of < 50 cm, which decreases the ease at which they could be excavated. For all other sorted units than the surface sand, their position under other sediment units also hampers the excavation potential. A sediment cover, for example a till cover, does not prevent the other sorted units from being excavated, but further studies would be needed to better evaluate the feasibility of such an undertaking.

Due to the reasons discussed above, only the surface sand out of the sorted sediment units in the model is discussed below considering the potentially excavatable masses. The total masses in the separate occurrences of the surface sand in the model range between 52 252 – 525 948 t. The largest occurrence is on the southern slopes of Kuusivaara, in the mass-flow area considered unreliable in the model due to the complex stratigraphy and insufficient data. Most likely the total volume of surface sand in that modelled occurrence is a mixture of sands, gravels and diamictons with varying geometries.

Excluding that occurrence, the largest body is on the western flank of Kuusivaara with an estimated total mass of 347 334 – 371 144 t. The volume to surface area ratio in that occurrence is 1:1.98 giving the body a mathematical average thickness of approx. 50 cm. As the sand is situated on the ground surface, organic soil can be expected to constitute more than 20 % (10 cm) of the theoretical volume. Taking that into account, the maximum total sand mass modelled on the western flank of Kuusivaara is approximately 300 000 t as a less than 50 cm thick surface cover (soil excluded) (Table 19).

The next largest occurrence is in the northeastern edge of Kuusivaara with an estimated total mass of 53 260 – 57 065 t. This body was modelled fully based on the superficial deposits map (GTK, 2018) and the thickness of the modelled body was estimated based on the surface sand occurrences in Pinoharju and the western flank of Kuusivaara. Thus, the mass estimation should be regarded as highly tentative and to acquire a more reliable estimate, the occurrence should be studied in the field.

The last surface sand occurrence in the cut-out was in Pinoharju with an estimated total mass of 52 252 – 55 985 t. The surface area of the modelled occurrence is more than three times the volume giving the body a mathematical thickness of approx. 30 cm. Taking into account the same consideration with an organic soil of at least 10 cm as before, the maximum total sand mass modelled in Pinoharju is approximately 37 000 t as a less than 30 cm thick surface cover (soil excluded).

Of the three till units present in the cut-out of the 3D model, only the upper sandy till can be considered potentially excavatable. The silty till is included in the cut-out only with a total estimated mass of 6 231 – 7 195 t situated close to the wetlands. It can be stated that there are no realistic silty till occurrences for potential excavation in the cut-out of the 3D model due to the small mass of the only modelled occurrence, the likelihood of groundwater being situated relatively near to the ground surface at a low elevation and the fact that the silty till occurrence is overlain by the upper sandy till.

For the lower sandy till, both occurrences in the cut-out have volume-to-surface-area ratios of less than 1:2.8 giving a mathematical average thickness of less than 35 cm. Considering that the occurrences are also overlain by the sorted sediments and upper sandy till, they can be assessed to not be potential for excavation. The low volume-to-surface-area ratios of the occurrences are a result of the 3 m cut-out depth (from the ground surface) used in confining the 3D model cut-out. Thus, better estimates of the excavation potential could be made by studying the actual groundwater level in the areas with the lower sandy till and using that data to determine a corrected cut-out depth.

The total estimated mass of the upper sandy till in the cut-out of the 3D model is very high, 23 892 480 – 29 245 440 t. The high estimated mass is due to the sediment unit covering most of the ground surface in Kuusivaara. Using the volume-to-surface-area ratio of approx. 1.1:1 for the upper sandy till in the cut-out, the mathematical average thickness is approx. 110 cm. Two factors are likely to affect this average: near the crest of Kuusivaara the modelled layer is relatively thin in the un-cut 3D model, and in the lower areas, where the modelled layer in the un-cut 3D model is thicker than 3 m, the cut-out depth of 3 m can reduce the total volume in the cut-out.

Table 19: The potentially excavatable masses of the surface sand and upper sandy till at those parts of the cut-out of the 3D model, where the modelled units are considered reliable. The estimated organic soil cover over the surface sand has been excluded from the mass values.

Sediment unit and location	Potentially excavatable mass (t)
Surface sand	
Western flank of Kuusivaara	300 000
Pinoharju	37 000
Upper sandy till	
Kuusivaara	23 892 480 – 29 245 440

The upper sandy till shows varying geotechnical properties in the *in situ* observations. For example, the washed nature of the unit and the proportion of larger clasts in the till varies. These differences were not taken into account in the 3D modelling. Lateral boundaries can most likely be determined for the variation of these properties, for example, by defining the area in the northwestern part of Kuusivaara, where the top parts of the till have been washed. Possible future excavation plans for the upper sandy till should consider the variation in the sediment properties and carry out more detailed studies to define more precise boundaries for the presence of the different qualities.

7.2 The stratigraphy of Kuusivaara

The only previously existing sedimentological descriptions and interpretations of Kuusivaara used in this study were those by Salonen *et al*. (2018) and Valkama (2018) from the southern side of Kuusivaara. They described two till units and sorted sediments both above and below the tills. Test pits excavated in this study, which were situated close to the test sites of Salonen *et al*. (2018), correlated well with their observations.

In this study and that of Salonen *et al*. (2018) and Valkama (2018), sandy till was observed with a relatively shallow bedrock surface depth on the western flank of Kuusivaara (test pits M1 and 20TR018). Closer to the crest of Kuusivaara on the western end of the hill, the observation of diamicton mixed with the weathered bedrock material in test pit M2 correlates well with the observations in the test pit 20TR025 of this study.

In the southeastern part of Kuusivaara, test pits M5 and M6 by Salonen *et al*. (2018) show a similar stratigraphy as the test pit 20TR027 of this study. All three show a succession of the loose, sandy till on the top, underlain by a layer of sand, and then a compact, more clast-rich sandy till at the base. This succession was not observed elsewhere in the study area. The sand and lower till below the upper sandy till could have been preserved during the last glaciation due to their location in the southeastern slope of Kuusivaara. As the general ice flow direction of the last glaciation, or till bed II by Hirvas (1991), was approx. northwest to southwest over the Kuusivaara area, the southeastern side of the hill could have been in the leeside of the ice flow and thus in the area of weaker glacial erosion. The till clast fabric measurements performed in the upper sandy till in this study did not show statistically significant orientations of clasts and therefore, an ice flow direction during the time when the upper till was deposited cannot be determined. However, the observations indicated a rough ice flow direction of west to east, which supports the hypothesis that the southeastern slopes of Kuusivaara were in the area of weaker glacial erosion and in the leeside of the ice flow.

The OSL age dating performed by Salonen *et al*. (2018) on a sand sample from the inter-till sand layer on the southeastern side of Kuusivaara yields an age of 70 000 ± 14 000 years BP. This would indicate that the lower sandy till observed in that area was deposited during the Early Weichselian or before that. The OSL age dating of the ice wedge cast in the test pit

20TR018 of this study yields a similar age (77 000 ± 15 000 years BP). This strengthens the evidence of an ice-free period in Kuusivaara during the Early Weichselian.

Salonen *et al*. (2018) did not observe the silty till unit that was observed in this study in one test pit on the southern side of the mire south of Kuusivaara and has previously been observed in three soil drilling sites on the mire. The silty till does not seem to be present at the higher elevations north of the mire areas south of Kuusivaara. The silty till could correspond with the till bed III described by Hirvas (1991) based on the blueish grey colour, finer matrix and position in the stratigraphy.

Only a few kilometres north of Kuusivaara, Åberg *et al*. (2017) describe three separate till units in their sedimentary 3D model and they assume the lowest till in their model to correspond to the till bed III described by Hirvas (1991). It seems possible that the lowest till in their study corresponds to the silty till observed south of Kuusivaara in this study. Given these correlations to the till bed III, the silty till south of Kuusivaara is possibly Early to Middle Weichselian.

The observations of the upper sandy till that is widely on the surface in Kuusivaara correspond well with the till bed II described by Hirvas (1991) in the ice divide zone as a sandy till with a scattered fabric, containing large amounts of weathered bedrock. This indicates that the upper sandy till in Kuusivaara was deposited during the last deglaciation. The varying properties observed in the till, such as the washed matrix in some areas, are interpreted to be post-depositional.

The mires surrounding Kuusivaara are peat-covered. Generally, sandy till is present under the peat cover. However, south of the drylands on the southern slopes of Kuusivaara, sand is found directly under the peat. This has been observed in one soil drilling site and widely in the GPR interpretations. In the 3D model of this study, the upper contact of this sand is uniformly at an elevation of approx. 190-192 m a.s.l. This correlates relatively well with the elevation of 195 m a.s.l. for the Moskujärvi ice lake during the phase when it drained through the Hirviäkuru gorge (Johansson, 2005). This may indicate that the widely occurring sands below the peat were formed during this ice lake phase, shortly after the last deglaciation. Furthermore, the sands in Pinoharju are at the elevation 195 – 200 m a.s.l. in the 3D model. It is likely that the sand observed on the surface at Pinoharju can be correlated with the Moskujärvi ice lake phase, since an ancient shoreline with a boulder rim was observed on the upper parts of Pinoharju during the test pit excavations and the surface sand in the test pit 20TR023 contained flow structures.

Based on the hillshade LiDAR image, at least some of the sands south of Kuusivaara on the mire areas are part of a deltaic formation that was created by the release of water from the drainage channels higher on the slopes of Kuusivaara. The drainage channels start at an elevation of approx. 204-205 m a.s.l. and therefore might also be related to the Moskujärvi ice lake, during a phase when the water level of the lake was at approx. 207 m a.s.l. and it drained to the River Luiro valley. On the slopes of Kuusivaara, the same drainage channels above the deltaic formation in the LiDAR are part of complex geomorphology created most likely by mass-flows and alluvial processes. The *in situ* observations in the mass-flow areas include sands, gravels, and diamicton.

On the western flank of Kuusivaara, the narrow zone of sands on the ground surface seems to be related to the River Kitinen as both north and south of Kuusivaara there are sands and eskers on the eastern bank of the river (GTK, 2018). Thus, previous channels and floods of the River Kitinen have most likely led to the deposition of the sands in the western part of Kuusivaara.

On the northern slope of Kuusivaara, a thick layer of gravel was observed below the topmost sandy till in the test pit 20TR022. The test pit location was chosen to study a southwest-northeast oriented ridge identified from the hillshade LiDAR image. Based on the test pit observation, the ridge that continues both south and north from the test pit in the hillshade image consists of considerable amounts of sorted sediments as well as till. The depositional environment of the ridge is unclear.

The six bedrock or weathered bedrock observations made in the 11 test pits of this study support the bedrock map, scale 1:200 000, by GTK (2017). In the bedrock map, Kuusivaara is presented consisting mainly of picritic volcanic rock and the bedrock in all six test pit observations was mafic volcanic rocks.

7.3 The geochemical characteristics of the sediments

The quality of the sampling and analysis of the geochemical samples collected from the test pits of this study was assessed by collecting duplicate samples in the field with identical sampling location, depth and methodology. In two of the three duplicate sample pairs, the differences in the geochemical composition of the samples are negligible. In one of the duplicate sample pairs, 20TR028.1 and 20TR028.1R, relative differences of 10-30 % between the samples are present in the concentrations of As, Cr, Cu, Ni and V in both analysed fractions. This could have been caused without human error, for example, due to the nugget effect. The geochemical sampling in the test pits of this study can be considered reliable, as two duplicate sample pairs produce very similar results and only relatively low differences are found in the concentrations of one of the three duplicate sample pairs.

The geochemical analysis results of the test pit and soil drilling samples with the two grain-size fractions, < 0.06 mm and < 2 mm, show that in the sediment samples the heavy metal concentrations in the finer grain-size fraction are significantly higher in comparison to the coarser fraction. Generally, the concentrations in the grain-size fraction < 2 mm range between 50.1 – 66.0 % of the concentrations in the grain-size fraction < 0.06 mm, excluding Hg, whose concentration in all the samples is very low.

In the weathered bedrock samples, the difference in the concentrations between the two grain-size fractions is much smaller. The concentrations in the grain-size fraction < 2 mm range between 76.2 – 110 % of the concentrations in the grain-size fraction < 0.06 mm, excluding Hg, which has very low concentrations.

The reactive surface area of the mineral particles in the finer grain-size fraction is larger, which can explain the difference in the concentrations. In addition, clay minerals adsorb heavy metals more effectively than most silicate minerals (e.g. Uddin, 2017). Since with the weathered bedrock the concentrations of the two grain-size fractions were relatively close to each other, this could indicate that there was only a small amount of material > 0.06 mm in the weathered bedrock samples and in both analysed fractions most of the material was actually smaller than 0.06 mm.

Comparing the median concentrations in sediment samples, the converted concentrations comparable to < 2 mm from the re-analysed drilled till samples (n = 90) are similar to the concentrations analysed with the actual grain-size fraction < 2 mm from the test pit and soil drilling samples (n = 45). The median concentrations differ for each element generally so that the converted median concentrations are 0 – 20 % higher than the median concentrations with the actual grain-size fraction < 2 mm. This indicates that the conversion produces relatively reliable estimates of the concentrations in the coarser fraction. The only element with a significant difference is Cu with the converted median concentration being 48 % higher than the concentration in the actual grain-size fraction < 2 mm.

Discussing the geochemical results with the combined population of both the actual < 2 mm samples' concentrations and converted < 2 mm concentrations provides a statistically larger sample population as well as wider spatial coverage of the study area. As the results are compared to the limits set in legislation to evaluate if the concentrations in the sediments exceed those limits, the possible overestimation in the converted concentrations can only lead to slightly more conservative conclusions.

For these reasons, the geochemical results are discussed below using the combined sample population of both the test pit and soil drilling samples in the grain-size fraction < 2 mm and the converted concentrations comparable to the grain-size fraction < 2 mm of the re-analysed drilled till samples. The term ‘limits set in legislation’ is used below to refer to the threshold limits set in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007) and when referring to Cr and Ni, the recommended background concentrations in Kuusivaara (GTK, 2020). When evaluating the statistical reliability of each subpopulation of samples, the lowest number of samples to provide acceptable reliability is considered to be 30 samples (SFS-EN ISO 19258:2018).

Considering first the sample population with all the sediment samples, regardless of the sediment unit in the 3D model which they were taken from, the size of the sample population (n = 135) is large enough for the results to be statistically reliable. The median and mean concentrations do not exceed the limits set in legislation for any element. For As, Co, Cr, Cu, Ni and V the median and mean concentrations are approx. 50 % of the limits set in legislation, and for all the other elements the concentrations are very low.

The maximum concentrations present in the individual sediment samples of the combined sample population exceed the limits set in legislation for As, Co, Cr, Cu, Ni and V. For As, Co and V the highest concentrations in the samples are approx. 50 % larger than the limits set in legislation. For Cr, Cu and Ni the highest concentrations are approx. 3-7 times higher than the limits set in legislation. These high concentrations in individual samples could be explained by, for example, sporadic grains of ore minerals (e.g. arsenopyrite, chalcopyrite) in the samples.

For the sample population with all the sediment units, the heavy metal concentrations are generally considerably below the limits set in legislation. The high concentrations in some individual samples are not likely to have a meaningful effect if the sediments are used as a mixed construction material.

Discussing the results separately for each of the sediment units in the 3D model, starting from the top of the stratigraphy, the small number of surface sand samples (n = 3) does not provide a statistically reliable sample population. Nevertheless, in the small sample population studied the limits set in legislation are not exceeded for any elements in any sample. For most elements, the concentrations in the surface sand samples are similar to the median and mean concentrations in all the sediment samples combined. In individual elements, there are differences of both slightly smaller and larger concentrations between the sample populations.

The upper sandy till samples are the largest sample population (n = 120) of the 3D model sediment units and the results for the unit can be considered statistically reliable. Median and mean concentrations for the upper sandy till samples are below the limits set in legislation for all elements. For As, Co, Cr, Cu, Ni and V, the median and mean concentrations are approx. 50 – 75 % of the limits set in legislation, and concentrations of the other elements are low.

The maximum concentrations in the individual upper sandy till samples exceed the limits set in legislation for As, Co, Cr, Cu, Ni and V. For As, Co and V, the highest concentrations in the samples are approx. 40 – 60 % larger than the limits set in legislation. For Cr, Cu and Ni, the highest concentrations in the samples are approx. 2.5 – 6.5 times the limits set in legislation.

For the upper sandy till, the concentrations of heavy metals are generally considerably below the limits set in legislation. The maximum concentrations in the results could be explained, for example, with the effect of mineralogy discussed earlier, but other factors could have an influence as well. Considering the variation of the properties observed *in situ* in the sediment unit, it is possible that the upper sandy till present in Kuusivaara is not uniform in geochemical composition over the whole study area. For example, the variations of the washed nature of the unit in some areas affect the grain-size distribution, which could in turn affect the geochemical composition, because it is evident from the analysis results, as stated earlier, that the finer grain-size fraction in the sediments contains more heavy metals than the coarser fraction.

The gravel samples are not present in the results with a statistically reliable population (n = 2). For the two samples, the maximum concentrations are considerably below the limits set in legislation with highest concentrations of As, Co, Cr, Ni and V comprising approx. 45 – 60 % of the limits set in legislation. The concentrations of the other elements are very low.

Only one inter-till sand sample was present in the analysis results (n = 1). The concentrations in that sample are significantly below the limits set in legislation, and for most elements also below the median and mean concentrations in all the sediment samples combined.

Statistical examination is not possible for the lower sandy till due to a low number of samples (n = 2). One of the two lower sandy till samples slightly exceeds the limits set in legislation for As and Ni.

The silty till samples are not present in the results with a statistically reliable population (n = 7). The median concentrations of silty till samples do not exceed any of the limits set in legislation, but the mean concentrations of Co and Ni exceed the limits by approx. 5 % and approx. 60 %, respectively. The maximum concentrations in individual silty till samples exceed the limits set in legislation for As, Co, Cr, Cu, Ni and V. For As, the maximum concentration is approx. 10 % over the limit and for Co, Cu and V the maximum concentrations exceed the limits with approx. 35 – 55 %. For Cr and Ni, the maximum concentrations are approx. 2.5 and 5 times the limits, respectively. Also, the highest Pb and Zn concentrations in silty till samples are significantly higher than concentrations of those elements in any of the other sediment units, but still only approx. 50 – 70 % of the limits set in legislation.

The weathered bedrock is discussed as last of the units in the 3D model. The number of weathered bedrock samples (n = 21) was not high enough to be statistically reliable but provides tentative estimates for concentrations in the unit. The median concentrations of the weathered bedrock samples exceed the limits set in legislation for Co, Cr, Ni and V, and the mean concentrations exceed the limits set for Co, Cr, Cu, Ni and V. In the median concentrations, the limits are exceeded with approx. 5 – 10 % for Cr and V, with approx. 50 % for Co, and with approx. 80 % for Ni. The median and mean concentration of Zn is also notably higher than in any of the other sediment units.

The maximum concentrations in individual weathered bedrock samples exceed the limits set in legislation for As, Cd, Co, Cr, Cu, Ni and V. For Cd, the limit is exceeded only barely, but for all the other elements listed the maximum concentrations are approx. 2 – 9 times higher than the limits set in legislation.

The notably higher concentrations in the weathered bedrock samples compared to the other units in the 3D model could be explained by enrichment of heavy metals in the bedrock during the pre-glacial weathering process. The very high maximum concentrations could be linked to samples containing considerable amounts of ore minerals, such as arsenopyrite, chalcopyrite and chromite.

The high concentrations in the weathered bedrock are most likely seen also as elevated concentrations in the sediments, mainly tills, that contain large amounts of material from the weathered bedrock. Pieces of weathered bedrock could also be a factor in the high maximum concentrations in individual samples of the upper sandy till and silty till.

The two-step batch leaching test was not performed on a sample population large enough to be statistically reliable (n = 18), but the results provide tentative estimates for the solubility of the elements from the whole sediment cover of the study area. The upper sandy till (n = 12) was the only sediment unit of the 3D model to be tested with more than one or two samples, and its results are discussed separately. The term ‘upper limit’ is used below to refer to the upper limit set for stable waste in the Government Decree on Changing the Government Decision on Landfills (202/2006).

For combined results of all the two-step batch leaching test samples, the median concentrations do not exceed the upper limit for any elements or substances. The median concentrations of TDS, Cr_{tot} and Ni are approx. 10 – 15 % of the upper limit, and the concentrations of the other elements and substances are very low. The maximum concentrations in individual samples exceed the upper limit for TDS, Cr_{tot}, Ni. For TDS and Ni, the highest concentrations exceed the upper limit with approx. 35 – 40 %, and the highest concentration for Cr_{tot} is approx. 3.5 times the upper limit.

The number of upper sandy till samples (n = 12) in the two-step batch leaching test results was not statistically reliable but considering that the samples were taken from varying depths with good spatial coverage of the study area, the results can be evaluated as tentative estimates for the soluble concentrations in the upper sandy till. The median concentrations in the upper sandy till do not exceed the upper limit for any element or substance. As with all the sediment samples combined, the median concentrations of TDS, Cr_{tot} and Ni are approx. 10 – 15 % of the upper limit, and the concentrations of the other elements and substances are very low. The maximum concentrations in individual upper sandy till samples exceed the upper limit for TDS and Cr_{tot}. For TDS, the upper is exceeded with approx. 40 % and for Cr_{tot} with approx. 20 %.

Comparing the geochemical analysis results with the two-step batch leaching test results, it is seen that Cr and Ni are among the elements exceeding the limits in legislation in both results. In the geochemical analysis results, Cr and Ni were among those elements, whose concentrations were multiple times the limits set in legislation in some individual samples. This could indicate that in the samples where higher solubilities for Cr and Ni were seen, the metals are not present in the sediments in especially soluble facies, but rather that the higher (total) geochemical concentrations of the two metals in the sediments lead also to higher soluble concentrations.

7.4 The water permeability of the sediments

Water permeability values were acquired in this study with two methods: *in situ* using slug tests and using estimates produced by empirical equations with grain-size distributions. The slug tests performed in eight different groundwater wells tested only two of the units in the 3D model of this study: the upper sandy till and the weathered bedrock. For those units, their water permeability is discussed below considering both the slug test results and values based on the grain-size distributions. For the other units in the 3D model, the discussion relies entirely on the water permeability values produced by grain-size distributions.

In the wells screened in the upper sandy till, the mean values of the water permeability results from the slug tests vary between $1.45 \cdot 10^{-7} – 5.60 \cdot 10^{-5}$ m/s. The lowest result, $1.45 \cdot 10^{-7}$ m/s, was measured in the well 18HYD026, where the screened section of the well is partially in peat and partially in the upper sandy till. The screened section begins at a depth of 2.5 m, and peat layers in several metres of depth generally have water permeabilities in the range of $10^{-9} – 10^{-7}$ m/s (e.g. Clymo, 2004). Thus, it is likely that the peat layer lowered the slug test results in the well 18HYD026 in comparison to the other wells screened in upper sandy till. The highest result, $5.60 \cdot 10^{-5}$ m/s, was measured in the well 17HYD005, where the screened section of the well is partially in sand and partially in the upper sandy till. In that well, the sand may have elevated the slug test results.

The well 17HYD003 is also not exclusively screened in the upper sandy till, but also in peat and sand. However, the peat section in the well is short, 1 m, in comparison to the full length of the screened section, 6 m. As the results from that well are in line with the other wells screened in the upper sandy till, it is possible that the short peat section did not decrease the result significantly, or that the screened sand (2 m) counterbalanced the low permeability of the peat with its generally higher permeability.

Excluding the results from 18HYD026 and 17HYD005, the water permeability results from the slug tests in the upper sandy till vary between $2.3 \cdot 10^{-6} – 1.7 \cdot 10^{-5}$ m/s. One unexplained phenomenon in the slug tests performed in wells screened in the upper sandy till was that in one well, 18HYD025, the results from the rising-head tests were one order of magnitude higher than the results from the falling-head tests. This phenomenon was not observed in any other well in this study and the reason is unknown.

The water permeability results obtained from the grain-size distributions of the upper sandy till show a range of $1.02 \cdot 10^{-5} – 1.55 \cdot 10^{-1}$ m/s. Values of 10^{-2} m/s and higher correspond to two samples of the upper sandy till that were taken from a notably washed upper part of the till near the ground surface. Generally, the values from the grain-size distributions were several magnitudes lower than 10^{-2} m/s. The abnormally high values are reflected in the mean water permeability obtained from the grain-size distributions, and for that reason the median values are regarded as the most reliable general estimate for the unit.

The median water permeability for the upper sandy till based on the grain-size distributions is $5.17 \cdot 10^{-5}$ m/s with the Kozeny-Carman method and $2.69 \cdot 10^{-4}$ m/s with the Sauerbrei method. These are relatively well in line with the slug test results for the same unit. The median with the Sauerbrei method is, however, one order of magnitude higher than any of the values in the slug tests.

Given the varying properties of the upper sandy till, a general range of water permeability for the unit is estimated at $2.3 \cdot 10^{-6} – 2.7 \cdot 10^{-4}$ m/s. However, coarser and washed parts of the unit are likely to have higher water permeabilities.

The former Finnish Road Institute (Tielaitos, 1993) estimated the water permeability range of sandy till to be $10^{-8} – 10^{-10}$ m/s, range of gravelly till to be $10^{-6} – 10^{-8}$ m/s, and the range of silty till to be $10^{-10} – 10^{-12}$ m/s. Ronkainen (2012) studied a large dataset of Finnish sediments and their water permeabilities based on laboratory studies. Excluding the lowest and highest 10 % of the values in that dataset to estimate the general water permeabilities, ranges for tills in the dataset are: $10^{-8} – 10^{-5}$ m/s for sandy till, $10^{-9} – 10^{-5}$ m/s for gravelly till, and $10^{-9} – 10^{-6}$ m/s for silty till.

Comparing the estimated water permeability of the upper sandy till to the data of Tielaitos (1993) and Ronkainen (2012) shows that the value acquired in this study for the upper sandy till is significantly higher than usual water permeability values for sandy tills, and in the upper range of gravelly tills as well. The slug test results for the upper sandy till are much closer to the ranges in literature and the tested groundwater wells are screened in the till several metres b.g.s. However, most of the grain-size distribution samples were collected from the looser upper parts of the sediment cover. Thus, it is possible that the slug test results provide a more reliable estimate for the upper sandy till situated in several metres depth, whereas the values based on grain-size distribution are more applicable for upper sandy till in the upper parts of the sediment cover.

In the wells screened in the weathered bedrock, the water permeability results of slug tests vary between $2.1 \cdot 10^{-6} – 1.2 \cdot 10^{-5}$ m/s. The grain-size distribution of the weathered bedrock was not determined in this study.

The water permeability of weathered crystalline bedrock varies greatly but is generally between $10^{-4} – 10^{-9}$ m/s in tests performed in borehole scale (Cook, 2003). The slug test results obtained in this study can be considered to be at a borehole scale and the results are within the range in literature.

Considering the factors affecting the slug test results, the double line effect described in *5.2.4 Slug tests* was particularly strong in the results from the wells 18HYD028, 18HYD030 and 18HYD033. This could be explained by the differences in the gravel pack and the screened section positioning between these three wells and the other tested wells. The three wells listed above have a long section (> 2.5 m) of gravel pack continuing around the well above the screened section, before the sealing bentonite pack near the ground surface. As such, there was a highly permeable layer through which the groundwater could have flowed in the beginning of the tests, and the flow from the undisturbed aquifer was dominant first after the gravel pack was saturated. The results of the other tested wells had only a slight double line effect or none, and the lengths of the gravel packs above the screened section were 0 – 0.5 m with the exception of the well 17HYD005, where the length was 2.0 m and no double line effect was present in the results.

Bouwer (1989) states that the double line effect should only be present if the groundwater table is below the screened section of the well. This was not the case in any of the three wells with prominent double line effect in this study. However, if the sealing bentonite pack does not begin directly above the screened section, it can be argued that the gravel pack continuing around the well upwards can act as a highly permeable storage for water in the beginning of the water level recovery, nonetheless.

As stated earlier, the water permeabilities for all the other units of the 3D model except for upper sandy till and weathered bedrock could only be estimated using the water permeability values calculated with grain-size distributions. The estimates discussed below for the other units of the 3D model can be regarded only as examples from the sediment units, since the number of samples used in the estimates varied between only 1 – 3 for each sediment unit.

For the surface sand, one grain-size distribution sample was present in the results with water permeability values of $2.69 \cdot 10^{-3}$ m/s and $2.11 \cdot 10^{-3}$ m/s with the Kozeny-Carman and

Sauerbrei methods, respectively. These values are well within the range presented for sands in literature (e.g. Ronkainen, 2012; Earle, 2019).

For gravel, three grain-size distribution samples were used and the results including both the Kozeny-Carman and Sauerbrei methods range between $9.69 \cdot 10^{-3} - 1.21 \cdot 10^{-1}$ m/s. These values are well within the range presented for gravels in literature (e.g. Earle, 2019).

For inter-till sand, one grain-size distribution sample was present in the results with water permeability values of $6.38 \cdot 10^{-5}$ m/s and $1.71 \cdot 10^{-3}$ m/s with the Kozeny-Carman and Sauerbrei methods, respectively. These values are within the range presented for sands in literature (e.g. Ronkainen, 2012; Earle, 2019).

For lower sandy till, one grain-size distribution sample was present in the results with water permeability values of $2.69 \cdot 10^{-5}$ m/s and $1.24 \cdot 10^{-4}$ m/s with the Kozeny-Carman and Sauerbrei methods, respectively. These are similar to the estimated water permeability for the upper sandy till. As discussed earlier regarding the upper sandy till, values in this range can be considered high for sandy tills. Further studies of the lower sandy till unit would be required to evaluate, whether the water permeability in the unit is generally as high as the values above.

As last of the 3D model sediment units, the silty till had two grain-size. The estimated water permeability range for the silty till using the Kozeny-Carman and Sauerbrei methods is $5.74 \cdot 10^{-6}$ m/s and $2.11 \cdot 10^{-5}$ m/s. These values are in the very high end for silty tills described, for example, by Ronkainen (2012). Similarly to the lower sandy till, further studies of the silty till unit would be needed to evaluate, whether this range describes the general range of water permeability for the unit.

8 Conclusions

Based on the *in situ* observations, a framework stratigraphy was created for the Kuusivaara area including the following nine units, listed beginning from the top: peat, surface sand, upper sandy till, gravel, inter-till sand, lower sandy till, silty till, (pre-glacial) weathered bedrock, and bedrock. A 3D model of the Quaternary sediments in the Kuusivaara area was created by modelling each of the units in the framework stratigraphy separately. GPR interpretations were used widely in the 3D modelling for the following units: peat, surface sand, upper sandy till, weathered bedrock, and bedrock. For the other units in the framework stratigraphy, the model results rely strongly on the *in situ* observations and geological interpretations. The 3D model results should be considered uncertain for the mass-flow affected area on the southern slope of the Kuusivaara hill, where the complex stratigraphy could not be modelled reliably.

The 3D model results show that outside the wetlands, the bedrock and weathered bedrock is overlain only by the upper sandy till in most of the Kuusivaara area. In limited, separate areas, the surface sand is present on the ground surface over the upper sandy till. In addition, in the mire areas south of Kuusivaara, the surface sand is widely present under the peat cover. The other sorted sediment units, the gravel and inter-till sand, are found below the upper sandy till in some areas in the northern, southern, and southeastern slopes of Kuusivaara. In most of those areas, the lower sandy till unit is found separated from the upper sandy till by the sorted sediment units. The silty till is overlain by the upper sandy till, and often peat, and the silty till unit occurs only south of Kuusivaara in the mire areas and in some dryland areas further south. Pre-glacial weathered bedrock is commonly found in the upper parts of the bedrock in Kuusivaara, but the 3D modelling could not reliably discern the weathered bedrock and bedrock apart. Thus, they should be considered as a combined unit in the model results, representing the bedrock regardless of its weathered or un-altered nature.

The surface sand and the upper sandy till proved to be the most potential sediment units in the model for excavation as a raw material. The potentially excavatable masses from those units were estimated only for the uppermost three metres from the ground surface in the dryland areas of the Kuusivaara hill. This was done to not include sediments, which are below the groundwater level (estimated at a depth of 3 m), into the excavatable masses. Excluding occurrences of the surface sand with insufficient modelling input data, the potentially excavatable masses of surface sand were estimated at: approx. 300 000 t as a less than 50 cm thick surface cover in the western flank of Kuusivaara and approx. 37 000 t as a less than 30 cm thick surface cover in Pinoharju. For the upper sandy till, a potentially excavatable mass of approx. 26 000 000 t was estimated over the Kuusivaara hill. Due to the variation in the physical properties observed in the upper sandy till over the study area, it is recommended that more detailed studies are conducted regarding the upper sandy till to produce better estimates.

The geochemical analysis results of the sediment samples show that the heavy metal concentrations in the grain-size fraction < 2 mm are generally approx. 50 – 65 % of the concentrations in the grain-size fraction < 0.06 mm. The ratios of the concentrations between the two grain-size fractions were used to convert heavy metal concentrations measured in the grain-size fraction < 0.06 mm to be comparable to the concentrations in the grain-size fraction

< 2 mm. The results show that the converted concentrations were generally approx. 0 – 20 % higher than the concentrations measured in the actual grain-size fraction < 2 mm, indicating that the conversion produces reliable estimates for the coarser fraction.

Comparisons of the heavy metal concentrations to the threshold limits in the Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007) and recommended background concentrations for Cu and Ni (GTK, 2020), could be performed with statistical reliability with two sample populations: all sediment samples from Kuusivaara combined and samples of the 3D model unit upper sandy till. For all the sediment samples combined, the median and mean concentrations do not exceed the limits set in legislation for any of the elements. The maximum concentrations in individual samples exceed the limits for As, Co, Cr, Cu, Ni and V. These elevated concentrations in individual samples can be attributed to many factors, for example, to sporadic grains of heavy metal-rich minerals in the samples.

The upper sandy till samples comprised most of the sediment samples (120/135 samples) and the results for that sample population were very similar to the results of all the sediment samples combined. Generally, the concentrations of heavy metals in the upper sandy till samples are considerably below the limits set in legislation, as indicated by the low median and mean concentrations in the results. High concentrations were found in individual samples. The heavy metal concentrations in the upper sandy till unit could vary based on its grain-size distribution, since the results show that the finer grain-size fraction of the sediments contains significantly higher concentrations of heavy metals than the coarser grain-size fraction.

Water permeability values were reliably estimated for two units of the 3D model: the upper sandy till and the weathered bedrock. The estimated range for the upper sandy till produced with the slug tests and grain-size distribution samples is $2.3 \cdot 10^{-6} – 2.7 \cdot 10^{-4}$ m/s. This is in the high end for the range of values given for sandy tills in literature (Tielaitos, 1993; Ronkainen, 2012). The upper sandy till unit is likely to have higher water permeabilities, where the unit is coarser and washed. The estimated range for the weathered bedrock produced with slug test results is $2.1 \cdot 10^{-6} – 1.2 \cdot 10^{-5}$ m/s. This corresponds well with the values in literature (Cook, 2003). The water permeability values produced with a few grain-size distribution samples from the other units of the 3D model correspond relatively well with the values reported in literature. However, the values for those units were in the high end of ranges, or higher than the average values, for the corresponding sediment facies in literature.

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